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Review

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Author for correspondence:
Jun Luo
e-mail: junluo@mail.hust.edu.cn

G measurements with time-of-swing method at HUST

Qing Li[1], Jian-Ping Liu[1], Hui-Hui Zhao[1], Shan-Qing Yang[1], Liang-Cheng Tu[1], Qi Liu[1], Cheng-Gang Shao[1], Zhong-Kun Hu[1], Vadim Milyukov[2] and Jun Luo[1]

[1]MOE Key Laboratory of Fundamental Physical Quantities Measurements, School of Physics, Huazhong University of Science and Technology, Wuhan, Hubei 430074, People's Republic of China
[2]Moscow State University, Sternberg Astronomical Institute, Moscow 119992, Russia

We review the G measurements with time-of-swing method at HUST. Two independent experiments have been completed and an improved experiment is in progress. The first G value was determined as $6.6699(7)\times10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$ with a relative standard uncertainty (u_r) of 105 ppm by using a long period torsion pendulum and two cylindrical source masses. Later, this result was corrected to be $6.6723(9)\times10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$ with $u_\mathrm{r}=130$ ppm after considering the density distribution of the cylinders and the air buoyancy, which was 360 ppm larger than the previous value. In 2009, a new experiment by using a simple block pendulum and spherical source masses with more homogeneous density was carried out. A series of improvements were performed, and the G value was determined to be $6.67349(18)\times10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}$ with $u_\mathrm{r}=26$ ppm. To reduce the anelasticity of the torsion fibre, fused silica fibres with Q's of approximately 5×10^4 are used to measure G in the ongoing experiment. These fibres are coated with thin layers of germanium and bismuth in turn to reduce the electrostatic effect. Some other improvements include the gravity compensation, reduction of the coating layer effect, etc. The prospective uncertainty of the next G value is 20 ppm or lower.

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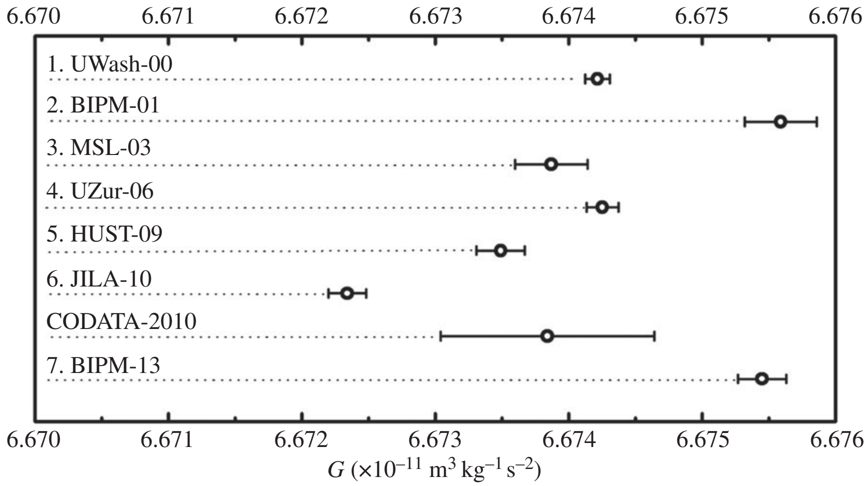

Figure 1. Seven G values with claimed uncertainties of less than 50 ppm [4–10] and CODATA-2010 recommended G value [3].

1. Introduction

(a) Background

The absolute measurement of the gravitational constant G was started about 200 years ago. The first G value was inferred from Cavendish's torsion pendulum experiment with $u_r = 1\%$ in 1798 [1]. During the past two centuries, more than 300 experimental G values were obtained with different methods [2]. The updated recommended G value by the Committee on Data for Science and Technology (CODATA-2010) was $6.67384(80) \times 10^{-11}$ m^3 kg^{-1} s^{-2}, with $u_r = 120$ ppm [3]. This status shows that the measurement precision of the G value was improved only at the rate of about one order per century, and it is still the worst among all the fundamental constants in nature.

Up to now, there have been seven G values with claimed uncertainties of less than 50 ppm (parts per million) published by different groups [4–10], as shown in figure 1. Gundlach & Merkowitz [4] presented the most precise G value with $u_r = 14$ ppm (UWash-00) by using the angular acceleration feedback method, which is slightly larger than G_{2010} (CODATA-2010 recommended G value, hereinafter the same). With the same test and source masses being adopted in two different methods, Quinn *et al.* [5] presented a G value (BIPM-01) which is greatly larger than the G values determined by any other group. Twelve years later, they rebuilt the apparatus and obtained a new result (BIPM-13) which agreed well with the previous value [6]. In contrast, Parks & Faller [7] found a G value with a simple pendulum by using a Fabry–Perot interferometer (JILA-10) which is 225 ppm lower than G_{2010}. The difference between the BIPM-01 (or BIPM-13) and JILA-10 results yields about 480 ppm, which is much larger than their claimed uncertainties. This bad coincidence can be attributed to the unfounded or incorrectly evaluated systematic errors in these measurements, which challenges experimental physicists to make a more reliable G measurement by further reducing systematic errors.

The beginning of determining G in our laboratory can be traced back to 1980s. The first result obtained by means of a very long period torsion pendulum and the time-of-swing method was reported in 1998 [11] and named as HUST-99 in the 1998 and 2002 CODATA adjustments [12,13]. In the following experiments, two systematic errors (the departure of the mass centre from the geometric one of the two cylindrical source masses and the effect of the air buoyancy) were found [14]. The revised G value was named as HUST-05 in the 2006 CODATA adjustment [15]. In 2009, we obtained a latest G value by using a rectangular glass block pendulum and two spherical

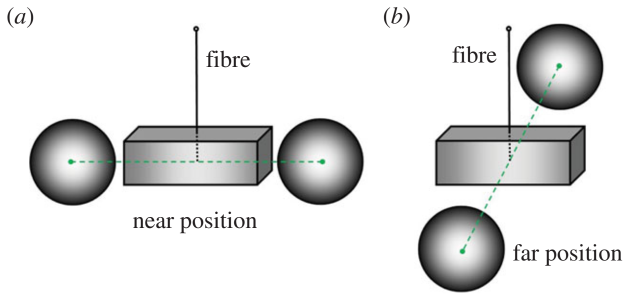

Figure 2. Sketch of the two positions of the pendulum and source masses in the time-of-swing method. At the near position, the pendulum's equilibrium position is in line with the centre line of the source masses (*a*). While at the far position, it is perpendicular (*b*). (Online version in colour.)

source masses with the same method [8,16]. This result was adopted by 2010 CODATA adjustment and named HUST-09. To further reduce the large corrections and uncertainties existing in the HUST-09 experiment, especially the so-called anelasticity of the torsion fibre, we perform a new G measurement by using high-Q (quality factor) fused silica fibres as well as a pure tungsten fibre. This paper presents the key features in HUST-99 (HUST-05), HUST-09 and the ongoing G measurements. For detailed descriptions of each experiment see earlier studies [8,11,14,16].

(b) Principle of the time-of-swing method

The time-of-swing method, first proposed by Braun in the 1890s and developed by Heyl, Cohen and Taylor later [17–20], has been widely used to measure G [21–23]. The basic principle of the time-of-swing method is to measure the change of the pendulum's period when the source masses are placed at two different positions, as shown in figure 2. At the near position, the pendulum's equilibrium position is in line with the centre line of the source masses which leads the period to become smaller. While at the far position, it is perpendicular and the period become larger. When considering the gravitational interaction due to the source masses, the motion of the pendulum can be described as follows:

$$I\ddot{\theta} + \gamma\dot{\theta} + K\theta = \tau_g, \tag{1.1}$$

where I represents the moment of inertial of the torsion pendulum, γ is the damping factor, K is the torsional spring constant of the suspension fibre and τ_g means the gravitational attracting torque acted on the pendulum, which can be expanded as follows:

$$\tau_g = -K_{1g}\theta - K_{3g}\theta^3 + O(\theta^5), \tag{1.2}$$

where $K_{1g} = \partial^2 V_g/\partial\theta^2|_{\theta=0} = GC_g$ and $K_{3g} = (1/6)(\partial^4 V_g/\partial\theta^4)|_{\theta=0}$, V_g is the gravitational potential energy between the pendulum and source masses, and C_g denotes the gravitational coupling coefficient which is determined by the geometrical metrology and mass distributions of the pendulum and source masses. For a small oscillation angle θ, K_{3g} and higher terms can be neglected, therefore $\tau_g \approx -K_{1g}\theta$ and the frequency squared ω^2 of the pendulum at two positions can be expressed as follows:

$$\omega_n^2 = \frac{K_n + GC_{gn}}{I}, \quad \omega_f^2 = \frac{K_f + GC_{gf}}{I}, \tag{1.3}$$

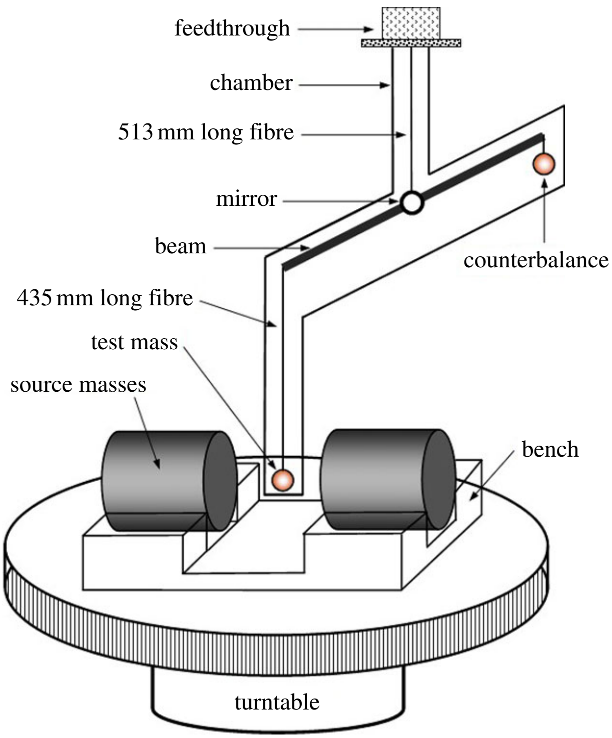

Figure 3. Schematic of the apparatus used in determining G of HUST-99 (in [11]). (Online version in colour.)

where the subscript 'n' and 'f' represent the near and far positions, respectively. For a torsion fibre with a limited Q, Kuroda predicted that its torsional spring constant K will change with the oscillation frequency [24], which means $K_n \neq K_f$. Thus G can be determined by:

$$G = \frac{I\Delta\omega^2 - \Delta K}{\Delta C_g}, \tag{1.4}$$

where $\Delta C_g = C_{gn} - C_{gf}$ and $\Delta\omega^2 = \omega_n^2 - \omega_f^2$ are the changes of the gravitational coupling coefficient and frequency squared between the near and far positions, respectively, $\Delta K = K_n - K_f$ represents the correction of the anelasticity of the fibre.

It can be seen that the G measurement with the time-of-swing method is based on the high precision measurement of the time instead of the weak force. In this method, the differential measurement between the two configurations is extremely useful to offset most of the same influences. The main disadvantages include the high requirement for the experimental environment and the dependence on the properties of the torsion fibre, such as anelasticity, thermoelasticity, nonlinearity, ageing, etc., which are important for a reliable result.

2. Determination of G at HUST

(a) HUST-99 G measurement and its correction

The apparatus of HUST-99 G measurement with the time-of-swing method is shown in figure 3. The source masses are two non-magnetic stainless steel cylinders with mass of 6.25 kg, length of 100 mm and diameter of 100 mm, which have been used by Chen *et al.* in the Cavendish laboratory of Cambridge [25]. The cylinders rest on opposite sides of the 32.26 g copper spherical test mass, which hangs from one end of a 404 mm long aluminium beam by a 25 μm diameter, 435 mm long

Table 1. One σ error budget in the HUST-99 G measurement (in [11]).

error sources	$\delta G/G$ (ppm)
source masses:	66
separation	62
density	17
mass	16
moment of inertia of pendulum	31
gravitational nonlinearity	8
$\Delta(\omega^2)$	75
total	105

tungsten fibre. Another copper sphere used as a gravitational counterbalance is suspended on the other end of the beam. The torsion pendulum hangs from the upper vacuum feedthrough by using a 25 µm diameter, 513 mm long tungsten fibre. A mirror is adhered on the middle of the beam to monitor the pendulum twist. The pendulum system is enclosed in a vacuum chamber at a pressure of approximately 2×10^{-5} Pa maintained by an ion pump.

The chamber is installed in a mu-metal shielded room with dimensions of $5 \times 3 \times 3.5\,\mathrm{m}^3$ upon a 24 ton shock-proof platform. The laboratory is located inside Yu-Jia Mountain, which stands to the north of HUST. The least thick area of the shield around the laboratory is more than 40 m, and the nearest exit is 150 m away. The average temperature in the shielded room is around 20°C all year round, and the daily change is less than 0.005°C without any additional control [26].

A series of related research is carried out to reduce the systematic errors and obtain the correct period for the pendulum, such as the thermoelasticity and nonlinearity of the torsion fibre and the data processing method, etc. [27–31]. Finally, the periods of the pendulum are measured to be about 4441 and 3484 s with and without the source masses in the far position, respectively, and the determined G value is

$$G = (6.6699 \pm 0.0007) \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}, \tag{2.1}$$

with $u_\mathrm{r} = 105$ ppm.

The error budget of the HUST-99 experiment is shown in table 1. It is shown that the main error sources consist of the separation of the source masses, the moment of inertia of the pendulum and the measurement precision of $\Delta(\omega^2)$, which bring in uncertainties of 62, 31 and 75 ppm, respectively. The separation of the two cylinders is adjusted and measured by using two equal-gauge blocks with uncertainties of 0.002 mm. To further reduce the uncertainty in the separation requires new source masses with higher machining precision. Using the present kind of torsion pendulum with slender beam, it is hard to improve the precision of the moment of inertia further. The main limiting factor of $\Delta(\omega^2)$ is that the pendulum's period is so long that it is vulnerable to outside vibrations, temperature fluctuations and so on.

In subsequent years, the details of the HUST-99 experiment were rechecked and two systematic errors were found [14]. One is the eccentricities of the mass centre from the geometric one of the two cylinders. Considering a linear density distribution along the axial direction, the eccentricities of the two cylinders are determined to be 10.3(2.6) and 6.3(3.7) µm, respectively, which contribute a correction of 210(78) ppm to the value of G. The other is from the air buoyancy when the source masses are moved out from the far position, which contributes a correction of 150 ppm. These two effects lead the HUST-99 G value to be 360 ppm larger, and the corrected G value is

$$G = (6.6723 \pm 0.0009) \times 10^{-11}\,\mathrm{m}^3\,\mathrm{kg}^{-1}\,\mathrm{s}^{-2}, \tag{2.2}$$

with the relative uncertainty increasing from 105 to 130 ppm.

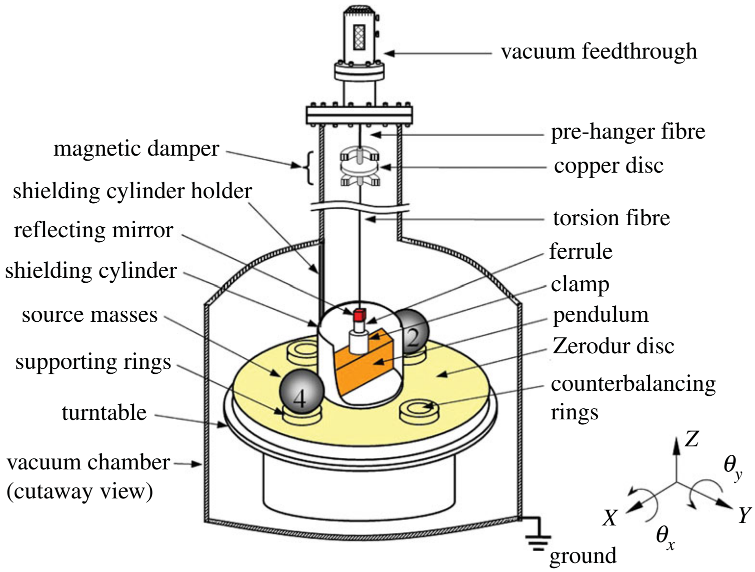

Figure 4. The schematic diagram of the pendulum system and source masses in HUST-09 *G* measurement with time-of-swing method (in [8,16]). (Online version in colour.)

(*a*) (*b*)

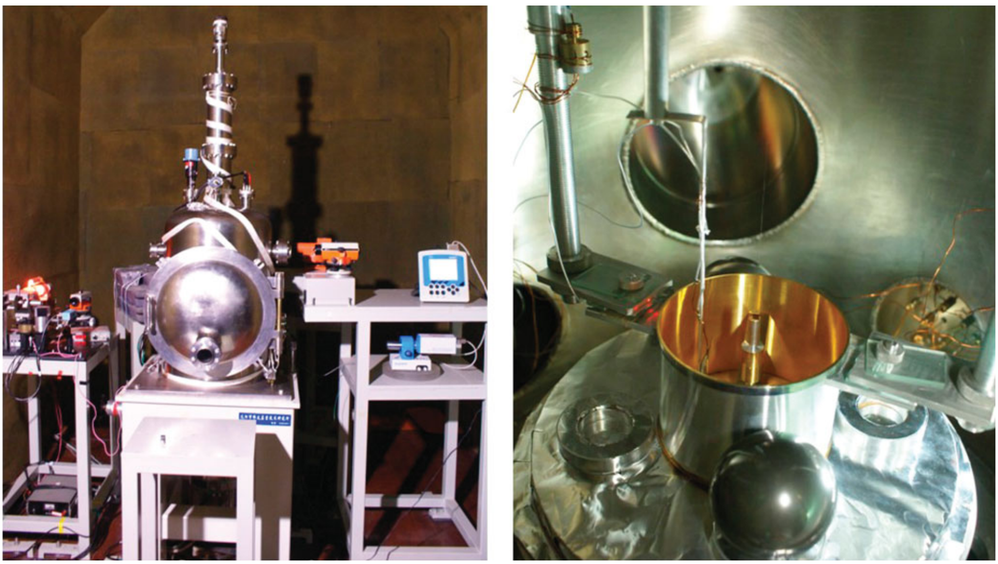

Figure 5. Photos (*a*,*b*) show the entire experimental apparatus and the pendulum and source masses in the vacuum chamber, respectively (in [8,16]). (Online version in colour.)

(b) HUST-09 *G* measurement

A great deal of evidence indicates that the measurement precision of the HUST-99 experiment is no more than 100 ppm; therefore, we designed a brand new experimental device to measure *G* still using the time-of-swing method [8,16], as shown in figures 4 and 5. A gilded rectangular glass block, whose dimensions and mass are 91.47 × 12.01 × 26.22 mm^3 and 63.38 g, respectively, is used as the torsion pendulum and hangs from a passive magnetic damper by using a 25 μm diameter, 890 mm long annealed tungsten fibre. The damper is suspended by a 50 μm diameter, 90 mm long pre-hanger tungsten fibre and used to reduce any tilt–twist coupling to the torsion fibre [32–34].

Two SS316 stainless steel spheres with diameters of 57.15 mm and vacuum masses of 778.18 g are used as the source masses. They are supported by two gilded identical Zerodur rings. The supporting rings together with two counterbalances are symmetrically adhered on a gilded Zerodur disc, which is mounted on a turntable driven by a remotely operated stepper motor. Because of the extremely low thermal expansion coefficient for Zerodur of $(0 \pm 1) \times 10^{-7}/^{\circ}\mathrm{C}$, the distance of the source masses is extremely insensitive to the temperature fluctuation during the experiment. To reduce the electrostatic effect and improve the period's stability, a gilded hollow aluminium cylindrical shielding is installed between the pendulum and source masses. The two-stage pendulum system as well as the source masses are installed in a vacuum chamber at a pressure of approximately 10^{-5} Pa maintained by an ion pump.

The main features in the experimental design of HUST-09 include:

(1) the spherical source masses are proved to have more homogeneous density than the cylindrical source masses used in previous experiments;
(2) the glass block pendulum with fewer vibration modes is helpful to improve the period's stability and the measurement precision of the moment of inertia;
(3) both the pendulum and source masses are set in the same vacuum chamber to reduce the measuring uncertainties of the relative positions and the air buoyancy;
(4) a remotely operated stepper motor is used to exchange the near and far positions to offset the environmental disturbances; and
(5) the anelasticity of 25 μm diameter annealed tungsten fibre is directly measured the first time [35].

Table 2 lists the one σ error budget in the HUST-09 G measurement. The uncertainty due to the torsion pendulum is only 5.07 ppm, which is one-sixth the HUST-99 experiment. By using an optical interference method, the correction due to the pendulum's coating layer is measured to be −24.28(4.33) ppm [36]. The largest errors of the source masses are attributed to their distance of the geometric centres. By using the rotating gauge block method [37,38], the distance is determined to be 157.16154(37) mm and introduces 9.64 ppm to the G value. The main uncertainty in distance is introduced by the roundness of the spheres, which are 0.23(3) μm and 0.27(3) μm, respectively. The density inhomogeneities of the source masses are studied by three different methods: (i) the eccentricities of the spheres are measured with the weighbridge method [39]; (ii) the sample sphere is cut into pieces and scanned using SEM [40]; and (iii) the positions of the spheres are exchanged and their orientations are changed deliberately, then the G measurement is repeated for the other subgroups individually. A difference of 9.00 ppm is found in two independent experiments, half of which is chosen as the error due to density inhomogeneities.

By using two disc pendulums with different moments of inertia assisted by a high-Q fused silica fibre, the anelastic effect of the tungsten fibre with Q of about 1.7×10^3 used in the HUST-09 experiment is first directly measured to be −211.80(18.69) ppm, which agrees with the upward fractional bias of $1/\pi Q$ proposed by Kuroda in 2σ [24] but smaller than the upper bound of $1/2Q$ predicted by Newman & Bantel [22,41]. The anelastic effect still contributes the largest uncertainty to G value in HUST-09 experiment.

The period change of the pendulum between the near and far positions is 3.23 s with a free oscillation period of about 535.2 s. Ten sets of experimental data with the source masses in near and far positions are taken alternately; after being corrected for the thermoelasticity, nonlinearity and background gravitational effect of the turntable, the combined statistical uncertainty of $\Delta\omega^2$ is determined to be 14.18 ppm.

Table 2. One σ error budget in HUST-09 G measurement (in [8,16]).

error sources	corrections (ppm)	$\delta G/G$ (ppm)
pendulum:		5.07
dimensions		1.95
attitude		0.13
non-alignment with fibre		0.45
flatness		0.34
clamp		1.65
density inhomogeneity		$\leq$0.21
coating layer	−24.28	4.33
edge flaw	−0.12	0.17
source masses:		10.68
masses		0.82
distance of GC		9.64
density inhomogeneity		4.50
XYZ positions		0.48
fibre:		18.76
nonlinearity		<0.70
thermoelasticity	−39.83	1.52
anelasticity	−211.80	18.69
ageing		<0.01
gravitational nonlinearity	7.73	0.30
magnetic damper	17.54	0.31
magnetic field		0.40
electrostatic field		0.10
combined statistical $\Delta\omega^2$		14.18
total		26.33

Finally, the combined G value in the HUST-09 experiment is found to be

$$G = (6.67349 \pm 0.00018) \times 10^{-11}\,\mathrm{m^3\,kg^{-1}\,s^{-2}}, \tag{2.3}$$

with $u_r = 26$ ppm. The most precise G value, determined with the time-of-swing method, is thus achieved.

(c) The ongoing G measurement

From the error budget of the HUST-09 G measurement, as shown in table 2, we can see that there are some notable corrections and uncertainties, such as the fibre's anelasticity, coating effect of the pendulum, gravitational nonlinearity, thermoelasticity, magnetic damper effect, etc. To further reduce these corrections and uncertainties in order to obtain a more reliable G value, a series of improvements is adopted in the following G measurement.

The anelastic effect is an important problem in G measurement with the time-of-swing method. As predicted by Kuroda, a direct approach to reduce the anelasticity is using a high-Q fibre. If $Q = 5.0 \times 10^4$, the anelasticity will be only −6.4 ppm. The inherent loss ($1/Q$) of the fused silica is

Table 3. The principal features in our G measurements.

items	HUST-99/HUST-05	HUST-09	ongoing experiment
pendulum system:			
shape	dumbbell	rectangular block	rectangular block
material	copper, aluminium	quartz	quartz
coating effect	—	−24.28(4.33) ppm	∼2 ppm
magnetic damper	—	17.54(0.31) ppm	∼0.4 ppm
u_r of pendulum	31 ppm	5.07 ppm	∼5 ppm
source mass:			
shape	cylinder	sphere	sphere
supporting	aluminium bench	zerodur ring	three-point mount
material	stainless steel	SS316 stainless steel	SS316 stainless steel
u_r of source mass	66 ppm	10.68 ppm	∼ 11 ppm
torsion fibre:			
material	tungsten	annealed tungsten	fused silica, tungsten
Q	3.6×10^4	1.7×10^3	5.0×10^4, 3.0×10^3
anelasticity	−9 ppm	−211.80(18.69) ppm	−6.4 ppm, −106 ppm
period:			
intrinsic period	3484 s	535.2 s	392 s and 535 s
period change	27%	0.6%	0.3%
u_r of $\Delta\omega^2$	75 ppm	14.18 ppm	expected less than 15 ppm
background gravity	no compensation	no compensation	compensation
temperature control	no extra control	no extra control	copper tube
$G(\times 10^{-11}\ \mathrm{m^3\,kg^{-1}\,s^{-2}})$	6.6699(7)/6.6723(9)	6.67349(18)	—

known to greatly lower than that of metals [42–44]. According to related research about various kinds of fused silica fibres [45], we chose the Heraeus fused silica with the trade name Suprasil 311 as the candidate of the torsion fibre to measure G, the trace impurity of which is less than 0.1 ppm. The fused silica fibres with diameters of 40–50 μm and length of 900 mm are pulled from 3 mm diameter fused silica rods by manual application of a oxygen-natural gas flame. The thickness variation of the pulled fibres over the middle section about 700 mm long is approximately 10%, and the Q's (quality factors) are about $(2\text{–}3) \times 10^5$. To suppress the electrostatic influence induced by the insulated fused silica fibre, based on the research reported by Numata *et al.* [46], the fused silica fibres are coated with 8 nm thick germanium and 11 nm thick bismuth in turn in our experiment. After coating, the Q's are reduced to approximately 5.0×10^4, which meets our original requirement. Moreover, from data recorded over 3 days, the period's stabilities of the coated fused silica fibres are better than 0.05 ms.

A number of other improvements are also carried out in the present G measurement, they are:

(1) the background gravitational field of the environment is measured by using a rectangular pendulum. After compensation with approximately 800 kg lead blocks, the influence on the period due to the background gravitational field is reduced to 1/5 of that before compensation. Besides, the equilibrium position of the pendulum in G measurement is located at the peak value of the background gravitational field, which leads to the least contribution to G value;

(2) to improve the stabilities of the positions of source masses, the three-point mounts are used to support the spheres in the present G measurement. The stabilities are measured with a capacitance monitoring system to be better than 0.2 μm;
(3) a copper tube with thickness of 5 mm is installed around the fibre to decrease the temperature discrepancy, and six sensors are installed near the fibre to monitor the temperature change. During the experiment, the largest difference between the sensors is less than 0.02°C, which contributes an uncertainty of less than 5 ppm to the G value;
(4) a fractional correction is introduced by the magnetic damper in the two-stage pendulum system. By adjusting the parameters of the suspension fibre, this correction is reduced from 17.54(0.31) ppm in the HUST-09 experiment to only 0.4 ppm now; and
(5) aluminium is chosen as the coating material of the pendulum instead of gold and copper, which are used in the HUST-09 experiment. Then the correction for the G value due to the coating layer is reduced from −24.28(4.33) ppm to less than −2 ppm.

So far, the above improvements have been generally accomplished and the data acquisition between the near and far positions is in progress. In the next 1 or 2 years, the G measurement will be carried out by using three different kinds of fibres in turn, two of them are fused silica fibres with diameters of 44 and 50 μm, the other is a 25 μm diameter pure tungsten fibre whose Q is approximately 3.0×10^3. The pure tungsten fibre for measuring G is chosen to verify the fibre's anelasticity. The prospective uncertainty of the final G value is 20 ppm or lower.

3. Conclusion

Our laboratory has focused on measuring the Newtonian gravitational constant G with the time-of-swing method by using precision torsion pendulums. Table 3 lists the principal features in HUST-99 (HUST-05), HUST-09 and the ongoing G measurements. The HUST-99 experiment has a considerable signal of the period change with and without the source masses in the far position, which yields 27%. The essential restrictions in the HUST-99 experiment include the separation between the cylinders and their eccentricities, the moment of inertia of the pendulum and measurement precision of the period.

To avoid the large corrections and uncertainties existing in the HUST-99 experiment, a number of improvements are adopted in HUST-09 G measurement. The anelasticity of the annealed tungsten fibre is first measured directly with the help of a high-Q fused silica fibre. The rectangular glass block pendulum with fewer vibration modes is proved to have a more stable period and greater measurement precision of the moment of inertia. The measured density inhomogeneities of the spherical source masses are much smaller than that of the cylindrical source masses. The environmental influences in this experiment are carefully regulated, such as setting the pendulum and source masses in the same vacuum chamber to reduce the air buoyancy and improve the measurement precision of the relative positions, exchanging the near and far positions by remote operation to lower the temperature fluctuation and vibration disturbance, etc. The shortcoming is that the relative change of the period between the near and far positions is only approximately 0.6%, which means that the requirement of the measurement precision of the period should be higher than that in the HUST-99 experiment.

The basic experimental design of the ongoing G measurement is similar to that of the HUST-09 experiment, the major difference is the use of high-Q fused silica fibres to measure G directly. We have prepared large numbers of fused silica fibres with diameters of 40–50 μm and length of 900 mm. After coating with 8 nm thick germanium and 11 nm thick bismuth in turn, the measured Q's are about 5.0×10^4, which introduce a correction of only −6.4 ppm to the G value according to Kuroda's prediction. To check out the dependence of G on the torsion fibre, besides using the fused silica fibres, we will also adopt the pure tungsten fibre with Q of approximately 3.0×10^3 to measure G, whose anelastic effect is about −106 ppm. The obtained G value with the pure tungsten fibre will be compared with that of fused silica fibres to verify the Kuroda hypothesis. Some other improvements are also carried out to improve the period's stability of the pendulum and reduce the potential systematic errors, such as the compensation of background gravity, the installations of the copper tubes and the three-point mount, etc. The purpose of all these endeavours is to obtain a more reliable G value at the level of 20 ppm with fewer systematic bias.

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