Research on dynamic swing experiment of atomic gravimeter based on the inertially stabilized platform

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Abstract. Based on the principle of quantum interference, with excellent accuracy, sensitivity, and stability, miniaturized and portable atomic gravimeters are gradually exploring the possibility of applying them to mobile platforms such as ships. However, the vibration noise brought by the dynamic environment has a great influence on it. To explore the stability and reliability of the atomic gravimeter in the mobile platform, we built a dynamic measurement system of the atomic gravimeter in the laboratory. With the help of the swing test bench, the swing of the roll and pitch directions was added to the system to simulate the wave environment, and the dynamic swing experiment was carried out. By changing different swing levels, the system can work in different vibration environments and measure the gravity value. The experimental results show that the atomic gravimeter can work normally in various swing environments, and the internal coincidence accuracy of 1.861 mGal is achieved. The measurement standard deviation of 2.194 mGal and the resolution of 1.160 mGal@48 s are obtained under static conditions. The measurement standard deviation of 34.200 mGal and the resolution of 9.538 mGal@48s are obtained under mixed swing conditions. Under the condition of mixed rolling, the standard deviation of the interference phase noise of the atomic gravimeter and its contribution to the resolution of gravity measurement reach 23.121 π mrad and 2.045×10^{-6} g/shot, respectively. Our work provides a new reference for the research of high-precision atomic gravimeters based on quantum sensing technology in the field of gravity measurement in ship-borne environments.

1. Introduction

Atom interferometer is an interference measurement technology like an optical interferometer. It uses atoms instead of photons as the main body of interference and uses laser pulses instead of beam splitting, beam combining mirror (π/2 pulse), and reflector (π pulse) as operating means. Finally, the process of beam splitting, reflection, and beam combining of atoms is realized, and the interference fringes are obtained by observing the change of the distribution probability of atoms on the two final state exit paths. An atomic gravimeter is a quantum sensor based on an atomic interferometer. The cold atom gravimeter at the beginning of the study has a huge volume and can only work in a static environment in the laboratory. In 1991, Professor Chu's research group at Stanford University realized the atomic gravimeter for the first time [1], and the resolution of gravity measurement reached 3×10^{-6} g. In recent years, with the deepening of research and the updating of technology, miniaturized and portable cold atom gravimeters have been gradually out of the laboratory, and their performance is basically comparable to the traditional best FG-5 absolute gravimeter. At present, most of the gravity measurement experiments of cold atom gravimeters are completed in low-noise quiet environments such as laboratories, suburbs, basements, and caves, while the early research work of dynamic gravity measurement of cold atom gravimeters is mainly flowing static measurement or ‘quasi-dynamic’ measurement. In 2016, the measurement sensitivity of the atomic gravimeter at Humboldt University in Germany reached 9.6 μGal/$\sqrt{\text{Hz}}$, the accuracy was about 3.9 μGal, and the long-term stability reached 0.05 μGal [2]. Its gravity measurement resolution and bias stability have exceeded the index of FG-5. In 2019, the University of California, Berkeley, used a portable atomic gravimeter for field gravimetry [3]. In the field environment, due to the large vibration noise, the sensitivity of the atomic gravimeter is about 0.05 mGal/$\sqrt{\text{Hz}}$, and the uncertainty of gravity measurement is about 0.04 mGal. Muquans, France, has realized the production of integrated atomic gravimeters. Its measurement accuracy reaches the order of μGal, the sensitivity is 50 μGal/$\sqrt{\text{Hz}}$, the long-term stability is 1 μGal, and the sampling rate is 2 Hz.

Dynamic gravimetry on moving carriers is an important application direction of atomic gravimeters. The French ONERA used an integrated atomic gravimeter to measure the dynamic gravity of a moving elevator [4]. The measured data are consistent with the data measured when the elevator is stationary in the range of 68 mGal, which proves that the atomic gravimeter can work properly on a moving platform. At the beginning of 2021, the Institute of Fine Measurement of the Chinese Academy of Sciences and the Naval University of Engineering completed the lake trial experiment of the atomic absolute gravimeter at the Mulan Lake Test and Training Base of the Naval University of Engineering [5]. A total of four voyages were carried out on the lake, sailing along the northern direction of Mulan Hunan. After filtering and deducting the Coriolis force of the earth, and using the ship-borne high-precision strap-down gravimeter (accuracy better than 1 mGal) as the navigation dynamic measurement benchmark, the measurement results show that the internal coincidence accuracy is better than 3 mGal. The external coincidence accuracy is better than 4 mGal.

More and more scientific research teams are committed to the measurement of atomic gravimeters in dynamic environments [6-8]. Therefore, to evaluate the measurement effect of an atomic gravimeter in a simulated wave environment and explore the robustness of the system to suppress vibration and noise, this paper designs the dynamic swing experiment of an atomic gravimeter based on an inertially stabilized platform. The inertially stabilized platform can keep the attitude stable, and the swing test bench can simulate the roll and pitch of the ship during navigation. Gravity measurement experiments are carried out under different swing states, and the gravity measurement results under a simulated wave environment are obtained. The influence of different vibration environments on the measurement performance of atomic gravimeters is analyzed and evaluated.

2. Experiment device

The dynamic swing experiment system of atomic gravimeter is mainly composed of an atomic gravimeter, inertially stabilization platform, swing test bench, shock absorber, differential GNSS system, control system, and data processing system. As shown in the figure, the key experimental equipment such as atomic gravimeter, inertially stabilization platform, and swing test bench are introduced.

2.1. Atomic gravimeter

The whole gravity device of the atomic gravimeter is composed of the physical system, optical system, and control system, as shown in Figure 1. The physical system is the area of atomic cooling and interference, which is mainly composed of a vacuum cavity, classical accelerometer, cooling and Raman laser beam, fluorescence imaging system, magnetic field coil, magnetic field shielding layer, and so on. The physical process is as follows [9]: firstly, the atom is cooled by a magneto-optical trap composed of a cooling laser beam and a MOT magnetic field coil to achieve three-dimensional cooling, and then the temperature of the atomic cluster is reduced to about 5 μK by polarization gradient cooling. After that, the magnetic field of the MOT coil and the cooling laser will be turned off, so that the atom falls freely in the vacuum cavity. Then, by adjusting the frequency of the laser and interacting with the atom, the atom is pumped from the cooling end state light to the initial state of interference, and then the laser frequency is continuously adjusted to form a vertical Raman laser. Through the interaction of π/2, π, π/2 Raman laser pulse, and atomic cluster, Raman interference is formed. The information on gravitational acceleration is stored in the material wave function of the atom in the form of an interference fringe phase. Finally, the frequency of the laser is changed to form a detection laser, which acts on the atom to form atomic fluorescence. The population of the atomic wave function is detected by normalized fluorescence imaging, and the signal is collected and stored by the control system.

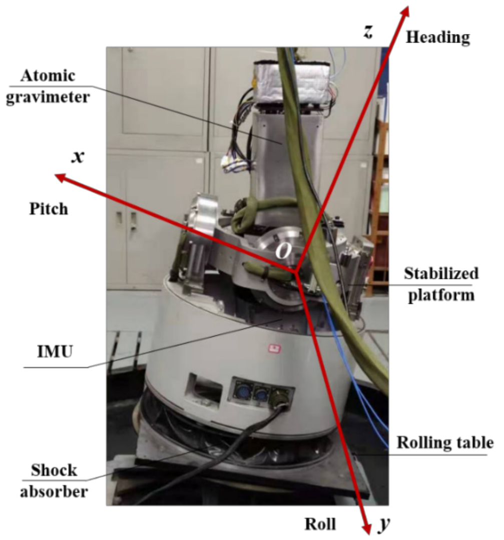

Figure 1. Dynamic swing experimental system of atomic gravimeter.

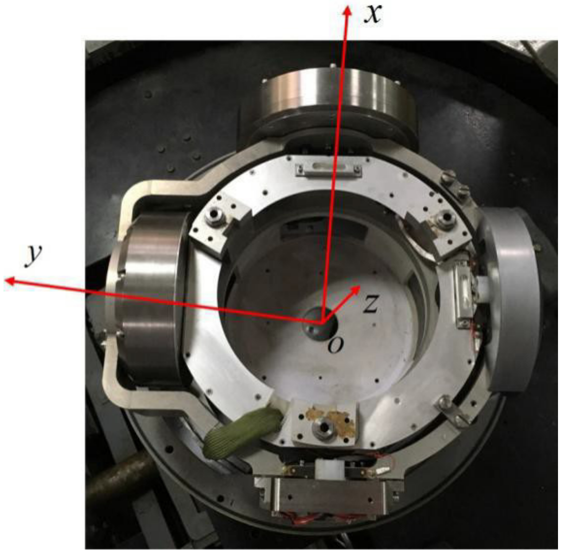

Figure 2. Inertially stabilized platform.

2.2. Swing test platform

The swing test bench can simulate the roll and pitch swing caused by the external environment such as waves during the navigation of the ship. The rotation and swing of each ring are controlled by the control system including the photoelectric encoder and the shaft end motor. The single swing is about 15 °, and the swing curve is basically a sine and cosine curve. In the experiment, the shock absorber and chassis at the bottom of the inertially stabilized platform can be fixed with the swing test bench, and the atomic gravimeter is placed on it to drive it to do pitching, rolling, and mixed rolling motion in turn. For the convenience of marking, Table 1 gives the identification of different swing levels, and the corresponding reciprocating period and maximum tilt angle.

Table 1. Identification of different swing levels.

Identification	Swing status	Single swing reciprocating cycle/s	Maximum tilt angle/°
N	Static, no swinging	0	15
P1	Pitch axis swings 1st level	40	
R1	Roll axis swings 1st level	40	
H1	Mixed rocking (pitch & roll) 1st level	30	
P2	Pitch axis swings 2nd level	27	
R2	Roll axis swings 2nd level	27	
P3	Pitch axis swings 3rd level	18	
R3	Roll axis swings 3rd level	18	

2.3. Inertially stabilized platform

An inertially stabilized platform, also known as a gyro-stabilized platform, is a device that uses a gyroscope to measure the azimuth of the carrier relative to ground motion in real time and keeps the azimuth of the platform unchanged through feedback control. In the dynamic swing experiment, its main function is to carry the atomic gravimeter. In the dynamic environment, the angular motion interference is isolated to provide horizontal reference and attitude information, so that the system maintains a stable vertical direction. At the same time, the angular vibration is attenuated to reduce the dynamic measurement error and provide a dynamic environment that meets the needs of dynamic measurement, to realize the gravity measurement of the moving base.

The inertially stabilized platform in this experiment is a biaxial structure with a pitch axis and a roll axis. The mechanical structure of the platform is shown in Figure 2. The performance of the platform can be tested by the swing test bench. Table 2 shows the performance index results obtained by the swing experiment. The swing test bench test shows that the performance of the stable platform can meet the needs of the swing test of the atomic gravimeter, and can complete the autonomous stable tracking function of its attitude.

Table 2. Test results of the inertial stabilized platform.

	Roll axis stability range	Pitch axis stability range	Roll axis stability accuracy	Pitch axis stability accuracy
Performance index	± 30°	± 30°	1′	1′

3. Experiment setting

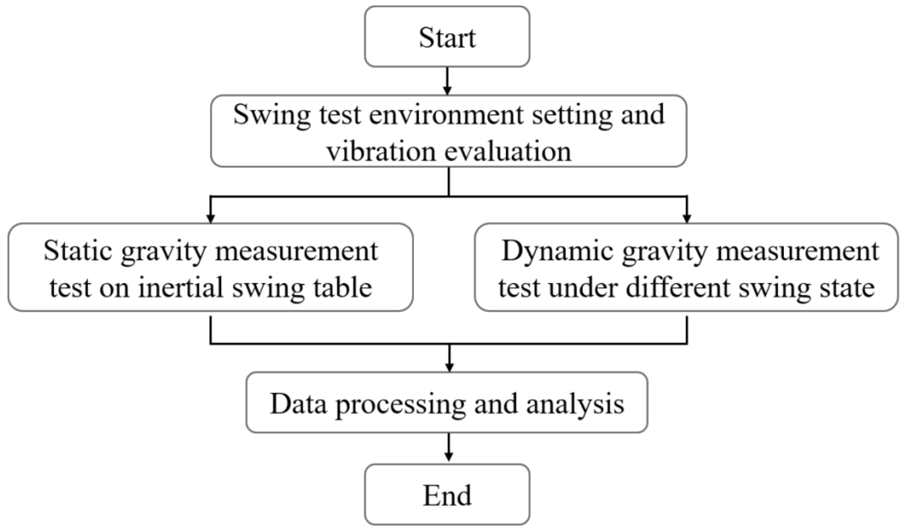

Figure 3. Basic process of experiment.

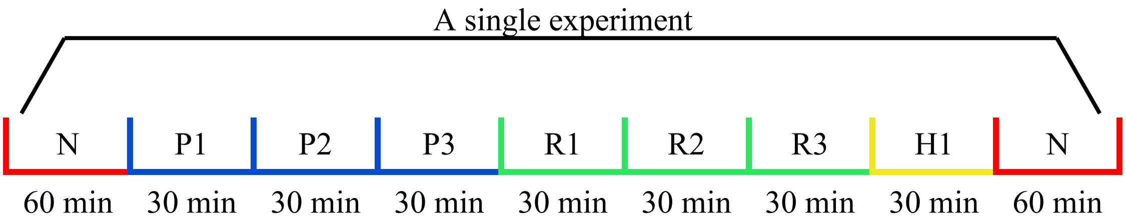

Figure 4. Time sequence of swing dynamic experiment.

As shown in Figure. 3, the specific experimental steps are as follows: firstly, the atomic gravimeter is placed on the inertially stabilized platform and the experimental environment is evaluated. After the experimental system is warmed up, the initial parameters are set, and the static gravity measurement experiment and the dynamic swing gravity measurement experiment are carried out respectively. The original data are recorded, and the data analysis and processing are carried out after the experiment is completed.

The dynamic swing experiment of the atomic gravimeter is carried out in the order of time shown in Figure 4. Firstly, the static base measurement is carried out for 60 min, so that the system is preheated and gradually enters the measurement state. After that, the swing test device is started, and the dynamic measurement of the pitch axis swing is performed three times in the order of 'P1-P2-P3'. The swing level gradually increases, and each measurement is 30 min. Then, the pitch axis swing is turned off, the roll axis swing is turned on, and the three-roll axis swing dynamic measurements are carried out in the order of 'R1-R2-R3'. Similarly, the swing level is gradually increased, and each measurement is 30 min. Then, the pitch axis swing and the roll axis swing are turned on at the same time, and the mixed swing mode H1 is entered and measured for 30 min. After the measurement, the static base measurement is performed for 60 min.

During the experiment, because the switching process between different states needs to be adjusted, there is a margin for the interception of the measurement time length to ensure that the measurement results are obtained under the stable working state of the experimental system, which is convenient for subsequent comparison and evaluation.

4. Result

4.1. Static base experiment

The experiment is carried out in a laboratory located in a busy urban area. The laboratory is located on the first floor, and the indoor personnel activities are more frequent. Therefore, the vibration noise is large, which belongs to a more complex vibration environment. The vibration noise amplitude will increase and the frequency band will be widened. Firstly, the power spectral density (PSD) of the ground vibration acceleration is measured as shown in Figure 5, and the vibration noise reaches a level close to $10^{-4}\,\mathrm{m\cdot s^{-2}/\sqrt{Hz}}$. The accelerometer Titan used to measure the vibration signal is a force-balanced triaxial acceleration sensor with a wide frequency band and a wide dynamic range. It has the extremely low self-noise performance of a broadband seismometer and has a small size, lightweight, and a large operating temperature range. When measuring, the inclination angle is adjusted to align the z-axis acceleration direction with the gravity acceleration direction. The range is set to 0.25 g, and the corresponding sensitivity is $8.16\,\mathrm{m/(s\cdot V)}$.

Considering that the measurement system, especially the atomic gravimeter, is very sensitive to the influence of environmental factors, the temperature of the measurement system is also detected. The temperature in the laboratory is about 23.5 ± 0.5 °C, the peak-to-peak value of the temperature change does not exceed 1 °C, and the gravity measurement results do not show mutations.

The whole system is installed, as shown in Figure 1. Before the start of the dynamic swing experiment, the gravity measurement test under the static base (without opening the swing test platform) is first carried out. The gravity value data and residuals shown in Figure 7 are obtained by continuous measurement for about 24 hours. The black point in the figure is the original measurement data, and the red curve is the gravity change curve calculated by the solid tide model. It can be seen from the figure that the peak-to-peak value of the gravity change after filtering is within 220 μGal, and there is no drift in the measurement results. The Allan deviation of the gravity measurement data is calculated to evaluate the sensitivity of the dynamic swing experimental system. It can be seen from Figure 6 that the sensitivity of the system is 353.6 $\mu\mathrm{Gal}/\sqrt{\mathrm{Hz}}$, and the resolution in 5 minutes integration time can be better than 24 μGal.

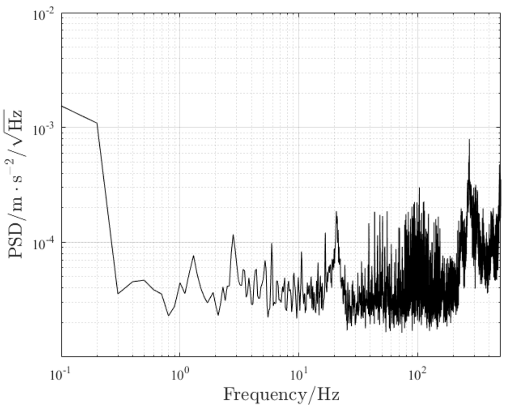

Figure 5. PSD of accelerometer.

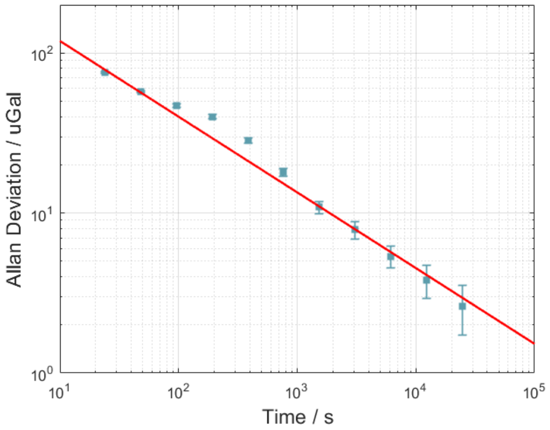

Figure 6. Allan deviation PSD (single point 5 minutes average).

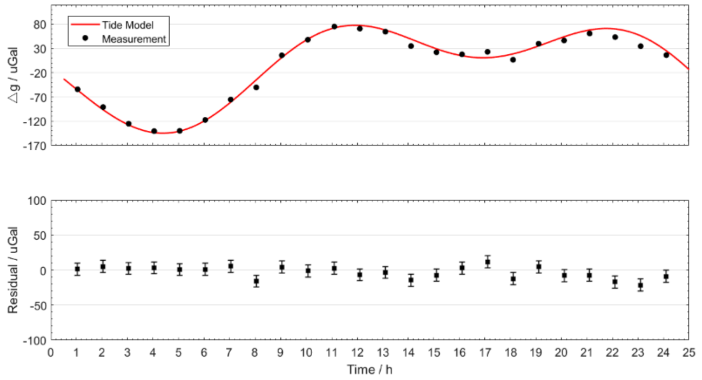

Figure 7. Gravity measurement results under static base (single point 60 minutes average).

4.2. Dynamic swing experiment

The interference time T of the atomic gravimeter is set to 15 min. The atomic interference fringes are recovered by vibration compensation technology, the phase and its uncertainty data are obtained by fitting the atomic interference fringes, and then the gravity value and its measurement uncertainty data are obtained. According to the established experimental scheme, for nine measurement states, we randomly selected the relatively stable gravity measurement data in the middle section of each measurement state with averaged measurement points every 12 s. In Figure 8, 30 continuous measurement gravity value points are marked. Among them, the error bar in the curve represents the standard deviation of gravity measurement, and different swing levels are marked in the figure.

It can be seen intuitively from the figure that different grades correspond to different swing intensities, which are approximately regarded as different simulated wave environments. The atomic gravimeter can output gravity values stably and effectively. For the same swing direction, with the increase of swing level, the dispersion degree of gravity measurement value is also increasing, and the corresponding standard deviation of gravity measurement is also increasing.

Table 3 quantitatively analyses the measurement results of the dynamic swing experiment. According to the measured mean values under different swing states, the calculated internal coincidence accuracy reaches 1.861 mGal. With the increase of the swing level, the standard deviation of the gravity measurement value increases from 2.194 mGal in the static state to 69.747 mGal in the

P3 level, and the gravity measurement resolution also increases from 1.160 mGal@48s in the static state to 22.185 mGal@48s in the P3 level. The effect of gravity measurement varies from each index, which also shows that the influence of vibration cannot be ignored and is basically positively correlated with the measurement results. The worse the vibration environment, the worse the stability of gravity measurement. Among them, the standard deviation of gravity measurement obtained in the swing state of the R2 level is less than that of the R1 level. One possible reason is that the system reaches a certain equilibrium state in the swing state of the R2 level, and the specific reason needs further analysis. In addition, the measurement resolution of the atomic gravimeter is improved.

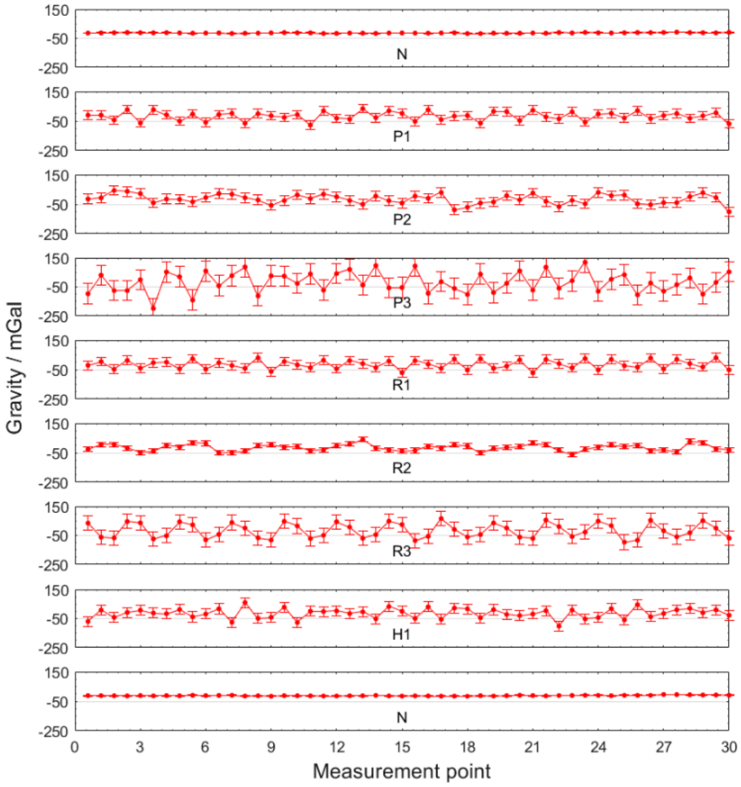

Figure 8. The results of gravity measurement under different rocking conditions.

Table 3. Analysis of gravity measurement results.

Swing status	Ave./mGal	Internal coincidence accuracy/mGal	Std./mGal	Resolution/ (mGal@48s)
N	g_0-12.6529	1.861	2.194	1.160
P1	g_0-16.3601		29.286	4.748
P2	g_0-15.8867		32.404	7.273
P3	g_0-17.5943		69.747	22.185
R1	g_0-15.4899		29.636	3.158
R2	g_0-15.4921		15.375	5.023
R3	g_0-16.6809		49.832	3.735
H1	g_0-14.2027		34.200	9.538
N	g_0-11.4752		2.621	1.368

4.3. Vibration analysis and evaluation

Vibration noise is one of the main noise sources that limit the sensitivity of cold atom gravimeters, and the influence on the Raman mirror is the most critical. The vertical vibration of the mirror will directly introduce noise into the interference phase. Therefore, in the dynamic swing experiment, the accelerometer is installed on the Raman mirror to accurately measure the vibration of the mirror under different swing states. Figure 9 compares the vertical acceleration values of the corresponding accelerometers under the P1, P2, and P3 swing levels. It is obvious that the higher the swing level, the greater the amplitude of the accelerometer, and the stronger the vibration. Figure 10 shows the vertical acceleration values of the corresponding accelerometers under the P1, R1, and H1 swing levels. The same is a level 1st swing, and the amplitudes of the three states correspond to the accelerometers. There is little difference, but in the H1 state, there will be a small number of sudden increases in amplitude, which indicates that the mixed swing state will become violent at some specific times. H1 may be closer to the real wave environment, and there are swings on both the pitch axis and the roll axis.

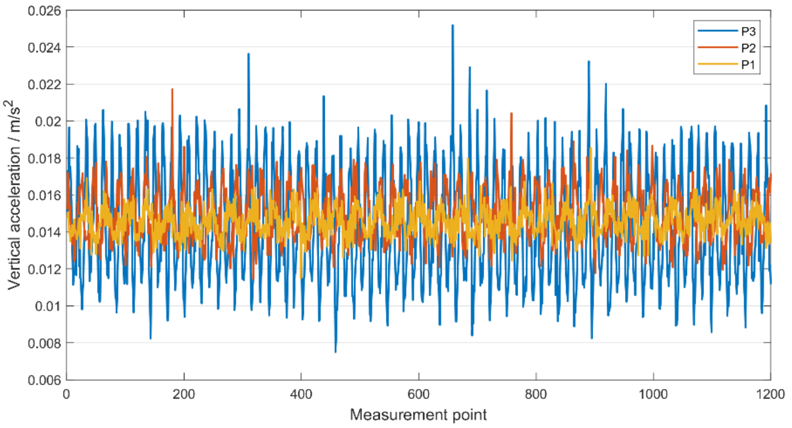

Figure 9. The vertical acceleration values of the corresponding accelerometers under the P1, P2, and P3 rocking levels (the average value of a single measurement at a single point).

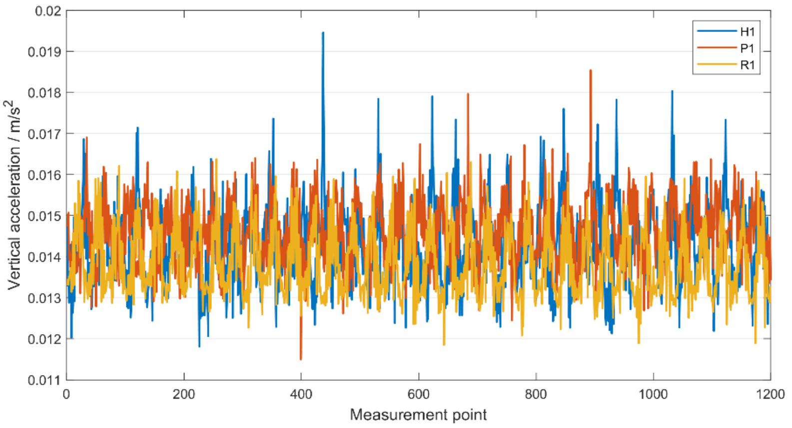

Figure 10. The vertical acceleration values of the corresponding accelerometers under the P1, R1, and H1 rocking levels (the average value of a single measurement at a single point).

To reflect the influence of different vibration environments more intuitively on the measurement performance of atomic gravimeters, combined with the transfer function of the atomic interferometer, we calculate the influence of vibration on the interference phase when the atom falls once. The influence of vibration noise and its contribution to gravity measurement can be evaluated by sensitivity function analysis. The power spectral density $S(\omega)$ can be calculated from the vibration acceleration signal $a_{vib}(t)$. The standard deviation of the interference phase noise caused by the vibration noise σ_{vib} can be expressed as:

$$\sigma_{vib}=\sqrt{\int_0^{\infty}\left|H_{\alpha}(\omega)\right|^2 S(\omega)d\omega} \tag{1}$$

It can be concluded from σ_{vib} that the contribution of the corresponding vibration noise to the resolution of the atom interferometry gravity measurement σ_g is:

$$\sigma_g=\frac{\sigma_{vib}}{k_{eff}T^2} \tag{2}$$

According to Formulas (1) and (2), the standard deviation of the interference phase noise of the atomic gravimeter and its contribution to the resolution of gravity measurement can be calculated in the dynamic swing experiment. As shown in Table 4, the standard deviation of the vertical vibration acceleration recorded by the accelerometer is represented by Std, and the size of Std reflects the severity of different swing levels. Under the condition of mixed swing, they reached 23.121 π mrad and 2.045×10^{-6} g/shot, respectively. In general, the Std under rolling conditions is much larger than that under static conditions and is 3-5 times as much as that under static conditions. For a single swaying, rolling or pitching, the higher the swaying level, the greater the Std. For the same grade of P1, R1, and H1, the Std of mixed swing is slightly larger than that of single swing, and the sum of H1 is also slightly larger than that of P1 and R1. Therefore, the vibration noise is also positively correlated with its influence on the atomic gravimeter. The higher the swing level (or mixed swing at the same level), the greater the standard deviation of the corresponding vertical acceleration, indicating that the stronger the vibration, the greater the interference phase noise caused by the vibration noise, and the greater the contribution to the resolution of gravity measurement.

Table 4. Quantitative analysis of the influence of vibration noise.

Swing status	Std./ ($\times10^{-3}$ m/s^2)	σ_{vib} /mrad	σ_g / ($\times10^{-6}$ g/shot)
N	0.210	6.606 π	0.584
P1	0.782	21.982 π	1.945
P2	1.423	25.580 π	2.263
P3	3.144	32.622 π	2.886
R1	0.798	20.504 π	1.814
R2	1.660	25.348 π	2.242
R3	2.770	30.881 π	2.731
H1	0.962	23.121 π	2.045

5. Conclusion

In this paper, a set of dynamic measurement systems of atomic gravimeters is built, and the dynamic swing experiment is carried out by simulating the wave environment with the help of the swing test bench. The experimental results show that the atomic gravimeter can work normally in various swing environments, and the internal coincidence accuracy of 1.861 mGal is achieved. The measurement standard deviation of 2.194 mGal and the resolution of 1.160 mGal@4s are obtained under static conditions. The measurement standard deviation of 34.200 mGal and the resolution of 9.538 mGal @48s are obtained under mixed swing conditions. Under the condition of mixed rolling, the standard deviation of the interference phase noise of the atomic gravimeter and its contribution to the resolution of gravity measurement reach 23.121 π mrad and 2.045×10^{-6} g/shot, respectively. Through the analysis and evaluation of vibration, the vibration noise is positively correlated with its influence on the atomic gravimeter. The higher the swing level is, or the more complex the swing is, the larger the standard deviation of the corresponding vertical acceleration is. The stronger the vibration is, the greater the interference phase noise caused by the vibration noise is, and the more the contribution to the resolution of gravity measurement is.

Although the vibration isolation air cushion fixed to the inertially stabilized platform can reduce the vibration noise in the high-frequency range to a certain extent, the accelerometer still needs to have high bandwidth to reduce the influence of residual noise. The bandwidth (-3 dB) of the accelerometer used in our experiment is from DC to 430 Hz. Due to the attenuation of the transfer function in the high-frequency band, it has been proven to be sufficient for vibration compensation under static conditions [10]. However, the high-frequency vibration noise at 430 Hz cannot be measured, which will amplify its influence on gravity measurement in a dynamic environment like the swing. In addition to the measurement bandwidth, the normalized transfer function of the accelerometer itself will not be constant above tens of Hz, which will lead to errors in measuring higher frequency vibrations. In addition, in the simulated wave environment through the swing test bench, the phase noise caused by the high vibration noise caused by the swing may span multiple atomic interference fringes, which will cause certain errors in vibration compensation. The follow-up research focuses on vibration suppression or compensation, and further improves the performance of the dynamic gravity measurement system through the combination of hardware and software.

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