Review on Vibration Isolation Method for Atomic Interference Gravimeter

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Abstract: The cold atomic interference absolute gravimeter is an ultra-precision instrument for measuring absolute gravity acceleration. At present, the highest measurement accuracy can reach the order of micro gamma. It has important application value and research significance in many disciplines, such as geophysics, resource exploration and assisted navigation. Because of its ultra-high precision, the ultra-low frequency micro-vibration noise on the ground has become one of the important factors affecting its accuracy, and it is also the bottleneck of the further development of gravimeter. Firstly, based on the theoretical and experimental results, this paper analyzes the vibration isolation requirements of atomic interference gravimeter. Secondly, it summarizes the research progress of atomic interference gravimeter isolation system and introduces three main isolation methods: passive vibration isolation, active vibration isolation and vibration compensation. Finally, the future development direction of atomic interference gravimeter isolation technology is analyzed and prospected.

1. Introduction
The absolute gravimeter based on cold atom interference has become a research hotspot at home and abroad with its ultra-high measurement accuracy, more and more extensive application scenarios and prospects. At present, the highest measurement accuracy of the absolute gravimeter can be stabilized at the order of 10⁻⁹g.

With the continuous improvement of the accuracy of the gravity measurement system, the low-frequency ground micro-vibration, which originally has a small impact, has become an important factor restricting the improvement of the measurement accuracy. During the measurement process, after the Raman light is introduced into the vacuum cavity by the optical fiber, it is reflected by the bottom mirror to form a pair of opposite Raman light. As the inertial reference of absolute gravity measurement, the vibration of the reflector will be transformed into the phase change of the laser, causing the system to introduce phase noise, reduce the signal-to-noise ratio of the measurement, and limit the measurement sensitivity.

Through a large number of principle analysis and practical tests, among the many measurement influencing factors, the vibration of the reflector has the greatest impact on the measurement results. Conventional vibration isolation systems are difficult to effectively suppress the ultra-low frequency vibration transmitted to the mirror from the ground. Therefore, this article summarizes and
summarizes a series of effective vibration isolation methods for the mirror vibration noise of the atomic interference gravimeter, and analyzes and prospects The future development direction of these vibration isolation methods. To further improve the accuracy of cold atom interferometric gravity measurement.

2. The influence of ground vibration and noise on absolute gravity measurement

Vibration noise that affects the measurement results can be roughly divided into two types: system noise and environmental noise.

Although system noise cannot be completely avoided, it will have a more obvious impact only in a quiet environment, and it can be reduced by optimizing the mechanical and circuit design. Therefore, it is the environmental noise that has a greater impact on the measurement result.

Environmental noise can be divided into ground vibration noise, acoustic vibration and directly applied load force [1]. The ground pulsation noise is caused by the free oscillation of the earth itself, and the frequency is low. It is not only unavoidable during the operation of the equipment, but also has an impact on the measurement. As a result, the impact is even greater and must be properly handled.

On the one hand, it can be seen from the vibration and noise acceleration power spectrum measured by the laboratory in Fig. 1 that there are multiple peaks in the range of 0.1-10 Hz, and the most serious is the ground pulsation noise around 0.3 Hz, and its influence is unavoidable. On the other hand, from Figure 2, the product of the vibration and noise transfer function and the power spectral density measured in our laboratory, it can be seen that starting from 10 Hz, low-frequency vibration and noise have a particularly large impact on the measurement results. In order to achieve higher precision measurement sensitivity, it is necessary to suppress vibration and noise in the low frequency range.

![Fig.1 Acceleration power spectrum of laboratory vibration and noise](image-url)
Fig. 2 Product of vibration noise transfer function and power spectral density

In summary, 0.01Hz-10Hz is the frequency band that has the most serious impact on the results of gravity measurement, and it is also the frequency band with the most serious ground pulsation noise. For this reason, the suppression of vibration and noise in this frequency band is the key goal of the vibration isolation system design.

3. Atomic interference gravimeter vibration isolation method

To sum up, 0.01Hz-10Hz is the frequency band that has the most serious impact on the gravity measurement results, and it is also the frequency band with the most serious ground pulse noise. Therefore, the vibration suppression in this frequency band is the key goal of the vibration isolation system design.

3.1. Passive vibration isolation

Passive vibration isolation is mainly achieved by using the spring structure and its special properties to reduce the characteristic frequency of the entire system.

3.1.1. Zero-length spring structure

Zero-length spring means that through a certain geometric design, the tension of the spring is proportional to the total length, which is equivalent to the original length of the spring before deformation is 0. And using this characteristic, the design structure makes the spring always in equilibrium no matter how the position of one end of the spring changes, that is, its intrinsic frequency is close to zero. Of course, due to the temperature drift and creep of the spring, as well as some unavoidable installation errors, the actual intrinsic frequency can reach about 0.05 Hz.

At present, there are already mature products based on zero-length spring improvement, such as Bell Lace metal zero-length spring automatic gravimeter, as shown in Figure 3; the classic up-throwing type IMGC-02 absolute gravimeter [2,3], a zero-length spring vibration isolation system is also used, as shown in Figure 4.
At present, compared with other passive vibration isolation structures, the zero-length spring structure is the most widely used. However, since the spring itself requires a certain length, the zero-length spring structure has a larger volume and will continue to accumulate due to the effects of temperature drift and creep. It is difficult to meet the vibration isolation requirements with miniaturization and mobility requirements. Therefore, the use of vibration isolation "springs" is constantly innovating.

3.1.2. Negative stiffness spring

The negative stiffness spring (Geometric Anti Spring, GAS) is a special structure that locally reduces the overall stiffness of the spring. The greater the spring stiffness, the stronger the load-bearing capacity, and the greater the eigenfrequency. The negative stiffness spring is connected in parallel with the positive and negative stiffness springs, so that the whole has nonlinear characteristics near the equilibrium position and the stiffness is close to 0. Reduce the eigenfrequency, but its overall load-bearing stiffness remains unchanged, so it can bear a larger load while obtaining a smaller eigenfrequency.

The most typical examples of the application of negative stiffness springs in vibration isolation systems are gravitational wave detectors such as LIGO and Virgo. It cleverly replaces springs with steel sheets and connects them in parallel through geometric design. Due to symmetry, the horizontal...
forces cancel each other out, and the load will only move in the vertical direction \[4\]. Its structure is shown in Figure 5 \[5\].

![Fig.5 Vibration isolator based on geometric anti spring](image)

The negative stiffness spring reduces the volume of the system by reducing the stiffness, and obtains a good vibration isolation effect under the condition of a large load. However, too small stiffness causes excessive spring displacement. Winterflood et al. used the Euler pressure rod in a critically unstable state as a negative length "spring" to solve the problem of excessive deformation under small stiffness, and then referred to the car chassis to design the torsion bar spring structure to reduce the complexity, but such a structure mechanical mechanism Design requirements and assembly requirements are very high, and long-term stability is difficult to guarantee.

3.2. Active vibration isolation

Although the use of the above-mentioned various structures can make the passive vibration isolation system obtain a lower intrinsic frequency, because they all use special physical and geometric characteristics, they generally have the problems of complex structure, large volume and difficult debugging. It is not conducive to the miniaturization of the system and it is difficult to meet the mobile requirements of the system. Therefore, active vibration isolation has become a better choice for some systems that pursue miniaturization and mobility.

Compared with passive vibration isolation, the biggest feature of active vibration isolation is the addition of feedback control of the driver, the use of sensing instruments to collect vibration signals, and the active control of the driver to offset the external vibration interference by the vibration isolation part.

3.2.1. Single-axis vibration isolation system

For Raman mirrors, the transmission of ground vibration and noise is mainly reflected in the vertical direction. For this reason, the single-axis vibration isolation system mainly needs to suppress the vibration in the vertical direction.

Under normal circumstances, passive vibration isolation has a better suppression effect on high-frequency vibration, but it is difficult to suppress low-frequency vibration; on the contrary, active vibration isolation is easier to suppress low-frequency vibration. Therefore, the active vibration isolation system usually adopts the combination of active and passive. The passive part suppresses mid- and high-frequency interference, and the active part isolates low-frequency vibration interference \[6-8\], so that the system can obtain a larger bandwidth under the same conditions.

Using active and passive vibration isolation methods, CHu \[9\] of Stanford University in the United States and the Freier team of Humboldt University in Germany have successively designed a set of vibration isolation systems for atomic interferometer gravimeters, with intrinsic frequencies reaching 0.033 Hz and 0.025 Hz, respectively. However, there are problems that the structure is too complicated and the assembly is difficult. In 2015, Tang Biao of the University of Chinese Academy of Sciences greatly simplified the structural complexity of the vibration isolation system based on the Freier team at Humboldt University. In order to ensure that the vibration and noise information
brought by the ground to the reflector can be more accurately collected by the seismometer, a set of aluminum bracket mechanical mechanism is designed. On the one hand, the coupling effect of horizontal vibration is reduced, and on the other hand, the various components are better connected. Better adjust the counterweight so that the center of mass of the vibration isolation part is in the best position of the platform for vibration isolation. The natural frequency of the improved system reaches 0.015 Hz, and the vibration around 1 Hz is reduced to $10^9 g / \sqrt{Hz}$ [10], and the overall vibration and noise are reduced by 100 times. The improved active vibration isolation system is shown in Figure 6.

Fig.6 Active vibration isolation of atom gravimeter designed by university of Chinese Academy of Sciences

3.2.2. Multi-axis vibration isolation system

Broadly speaking, the emergence of multi-axis vibration isolation systems is mainly based on two reasons. On the one hand, it is to adapt to the measurement during land, sea and sky movements, and to ensure that the system maintains a good posture while also suppressing external interference; On the other hand, in order to further improve the vibration isolation effect of the vibration isolation system, it is necessary to consider the phenomenon of vibration coupling, study its laws, and adopt appropriate multi-axis control methods to suppress it.

In order to solve the measurement problem of the system in a complex environment, researchers have developed a multi-axis vibration isolation system that can realize multi-dimensional motion in space. Most of the platforms are based on parallel structures. Under the joint action of multiple drives, the multi-dimensional interference transmitted to the load platform can be isolated. For example, a 3-axis micro-vibration isolation platform is used to isolate two rotational and one translational disturbances, or 3 mobile disturbances [11]; a 6-axis micro-vibration isolation platform is used to isolate interferences in any direction in space. Stewart vibration isolation system in "cube" configuration is the most typical example, and its schematic diagram is shown in Figure 7.

Fig.7 Stewart active vibration isolation platform

For the vibration isolation system in the laboratory, in order to achieve a better vibration isolation effect, the vibration in the horizontal direction must be considered at the same time. In order to obtain the coupling law of the horizontal vibration noise and the vertical vibration noise, and obtain the influence of the horizontal vibration noise on the measurement results, a lot of theoretical analysis and experimental verification must be passed. In 2016, Minkang Zhou’s team from Huazhong University
of Science and Technology improved the active feedback vibration isolation system. Through experiments, the law of vibration coupling was summarized and three-dimensional active feedback vibration isolation was achieved. The vertical intrinsic frequency reached 0.01Hz and the horizontal intrinsic frequency reached 0.083Hz. This three-dimensional system reduces the vertical vibration noise in the range of 0.2 to 2 Hz to 1/50 of the original, and the horizontal noise of the same frequency band to 1/5, and analyzes the impact of horizontal vibration noise on the gravimeter [12]. The structure of the three-dimensional active vibration isolation system is shown in Figure 8.

![Fig.8 Three-dimensional active vibration isolation system](image)

### 3.2.3. Secondary vibration isolation system

Active vibration isolation systems can also be divided into primary and secondary active vibration isolation systems according to the principle of the model. It uses the two-stage spring vibrator model to regard the two-stage spring as the upper and lower parts of the spring, which can actively control the deformation of the first-stage spring to be as equal as possible to the deformation of the other stage, simulating an infinite spring, and achieving lower intrinsic characteristics. Frequency, but inevitably also has a more complex structure.

The Superspring proposed in 1983 by Rinker from the JILA laboratory in the United States is a two-level active vibration isolation system [13] based on this design idea. The intrinsic period can reach 30s-60s, and the system has a very good vibration isolation effect. However, the system structure is too complicated [14], which is not conducive to the development of miniaturization and mobility of the system. So far, domestic and foreign laboratories are still continuously simplifying the complex structure of the secondary vibration isolation system, and have achieved a series of results [15,16].

### 3.3. Vibration compensation

The vibration compensation method is a method that can achieve vibration and noise suppression without a mechanical structure. Without a complicated structure, it can further improve the accuracy of gravity measurement and promote the development of miniaturization and movable gravimeters. This method is based on the principle of atomic interference gravity measurement, and through a certain compensation method, the error caused by the vibration and noise of the mirror is removed from the final measurement result, thereby reducing the measurement error. The vibration compensation method has different implementation schemes in the research of different institutions:

The more commonly used scheme is shown in Figure 9. During the experiment, the Raman light mirror at the bottom is installed above the accelerometer to monitor platform vibration and evaluate vibration and noise. During installation, the accelerometer should be as close as possible to the reflector and be precisely leveled. The longitudinal output signal of the sensor can be approximated as the vibration signal of the reflector after passing through the analog-to-digital converter and digital filter. Through the sensitivity function corresponding to the vibration acceleration, we can calculate the phase shift produced by the vibration in a measurement period. Finally, the phase shift is
compensated to the phase-transition probability curve to reconstruct the fringes and obtain the actual gravitational acceleration.

In order to verify the optimization effect of vibration compensation on the measurement results, the rubidium atomic interferometer gravimeter designed by Hannover University[17] carried out vibration compensation experiments in a noisy environment, using an ultra-wideband seismograph (Trillium 240) for vibration compensation, and setting free evolution time \( t \) is 78ms, which increases the short-term uncertainty from \( 4.4 \times 10^{-6} \text{ m/s}^2 / \sqrt{\text{Hz}} \) to \( 9.2 \times 10^{-7} \text{ m/s}^2 / \sqrt{\text{Hz}} \). It can be obtained from the experimental comparison of Hannover University that the simple vibration compensation method can achieve the same vibration isolation effect as passive vibration isolation. Compared with the vibration isolation method based on the mechanical structure, the biggest advantage of the vibration compensation method is that when the external disturbance is large, it can better realize the high-precision gravitational acceleration measurement, and it has a good effect on the vibration in the whole frequency band. The optimization has important practical application significance for the measurement of acceleration of gravity in the harsh environment of the field. However, real-time high-precision vibration compensation is very difficult to achieve, and it is still difficult to achieve high measurement accuracy with a single vibration compensation method.

4. Conclusion and Outlook

In general, passive vibration isolation systems can withstand larger loads, but they usually have larger natural intrinsic frequencies and simple principles. They are passive vibration isolation systems and are not limited by energy. However, if you want to obtain a lower intrinsic frequency, the structure will inevitably be complicated; and the assembly and debugging requirements are higher, and the debugging is difficult; because passive vibration isolation uses the mechanical and physical properties of the material, the material itself has creep And the problem of being susceptible to environmental temperature, the system's anti-interference ability is poor, and it is difficult to maintain long-term low-frequency operation. The anti-interference ability of the active vibration isolation system has been improved, and it can be adjusted according to different usage requirements. It has good low-frequency vibration isolation performance, and the assembly requirements and structural complexity are relatively low; however, active vibration isolation generally depends on complicated control algorithms, and need to be adjusted according to the actual situation, the design is difficult, and the effect of high-frequency vibration suppression is poor; the secondary active vibration isolation system is more complex in structure, technically difficult, and larger in size, but it has relatively best performance, can achieve stable work for a long time, and can be used in systems that do not require too much volume but pursue higher precision, such as the Superspring developed by Micro-GLaCoste in the United States. The vibration compensation scheme can adapt to complex environments and does
not rely on complex mechanical structures. It can better reduce the volume of the system, but the accuracy is lower, so it is suitable for field measurements that do not require high accuracy.

The classification of various vibration isolation methods and their typical cases are shown in Table 1 below. In the table, the volume and structure are divided into five levels from small to large, from simple to load (from 1 to 5).

At present, my country has made significant progress in the field of ultra-low frequency vertical vibration isolation systems. Related laboratories have also developed and improved vibration isolation systems based on different principles, and have continuously tested their effects and improved them in actual measurements. The development of these systems is expected to continuously improve the portability, reliability, stability and measurement accuracy of the gravity measurement system.

| Program         | Principle                 | Case             | Eigenfrequency /Hz | Volume | Structure | Features                                                      |
|-----------------|---------------------------|------------------|--------------------|--------|-----------|----------------------------------------------------------------|
| Passive         | Zero-length spring        | IMGC-02          | 0.05−0.07          | 5      | 5         | Passive system, low failure rate, large load capacity, but complex structure, large volume, difficult debugging, poor anti-interference ability, and poor long-term stability |
|                 | Negative stiffness spring | Stochino         | 0.03-0.08          | 3      | 3         |                                                                |
|                 | Euler pressure bar        | Winterflood      | 0.05               | 4      | 3         |                                                                |
|                 | Torsion bar spring        | Huazhong University of Science and Technology | 0.05 | 3 | 3 | Passive system, low failure rate, large load capacity, but complex structure, large volume, difficult debugging, poor anti-interference ability, and poor long-term stability |

| Initiative       | Single axis active        | University of Chinese Academy of Sciences | 0.015  | 2 | 2 | Active, high failure rate, small size, small load, good long-term stability, but poor high frequency suppression, requiring complex control methods |
|------------------|---------------------------|-------------------------------------------|--------|---|---|------------------------------------------------------------------|
|                  | Triaxial                  | Huazhong University of Science and Technology | 0.01   | 2 | 3 |                                                                |
|                  | Multi-axis                | Stewart                                    | 0.02-0.03       | 4      | 4      | No need for mechanical structure, adapt to harsh environment, can cooperate with other vibration isolation, but the accuracy is low, the design is difficult |
| Vibration        | Vibration compensation    | Hannover University                        | /      | 1      | 1      |                                                                |
| compensation     |                           |                                            |        |        |        |                                                                |

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