

Development of airborne gravity gradiometer based on a quartz flexible accelerometer

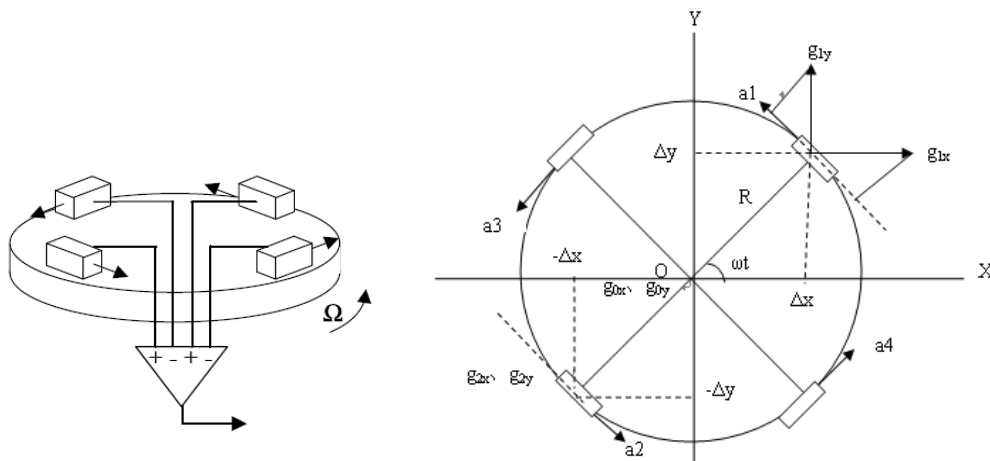
Zhaohai Meng¹, Ye Yang¹, Zhong Li¹

¹ Tianjin Navigation Instrument Research Institute, Tianjin, 526468457@qq.com

1. Progress in gravity gradiometer development

1.1 Working principle

The core component of a gravity gradiometer is a gravity gradient sensor. The gravity gradient sensor developed by Tianjin Institute of Navigation Instruments adopts a differential measurement technique of rotating accelerometer to realize a common mode suppression of motion acceleration and differential extraction of a gravity gradient signal. The main body of the sensor is a rigid platform with four symmetrically mounted low noise and high resolution accelerometers (a_1 , a_2 , a_3 , a_4). Four accelerometers are at the same distance from the center of the device. The input axis is perpendicular to the central rotation axis along the tangent direction of the platform plane. The two pairs of accelerometers are perpendicular to each other. Two independent gravity gradient tensors in the plane of the platform can be measured when the device rotates around a fixed rotation axis. The sum of the outputs ($a_1 + a_2$) and ($a_3 + a_4$) of a pair of accelerometers with relative mounting positions will eliminate the linear acceleration perpendicular to the axis of rotation, and the difference between the outputs of the two pairs of accelerometers $[(a_1 + a_2) - (a_3 + a_4)]$ will eliminate the angular acceleration around the axis of rotation, and the gravity gradient signal can be obtained by demodulating the sum and difference of the outputs of the accelerometers. In order to measure the gravity gradient on a moving base, the gravity gradient sensor needs to be placed on an inertial stabilized platform with gyroscopes and accelerometers.



$$T_{xOy} = \begin{bmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{bmatrix} \quad \begin{aligned} \Delta x &= R \cdot \cos \omega t \\ \Delta y &= R \cdot \sin \omega t \\ T_{xy} &= T_{yx} \end{aligned}$$

$$\begin{aligned} g_{1x} &= g_{0x} + T_{xx} \cdot \Delta x + T_{xy} \cdot \Delta y \\ g_{1y} &= g_{0y} + T_{yx} \cdot \Delta x + T_{yy} \cdot \Delta y \\ a_1 &= -g_{1x} \cdot \sin \omega t + g_{1y} \cdot \cos \omega t \\ &= -(g_{0x} + T_{xx} \cdot \Delta x + T_{xy} \cdot \Delta y) \cdot \sin \omega t + (g_{0y} + T_{yx} \cdot \Delta x + T_{yy} \cdot \Delta y) \cdot \cos \omega t \\ g_{2x} &= g_{0x} + T_{xx} \cdot (-\Delta x) + T_{xy} \cdot (-\Delta y) \\ g_{2y} &= g_{0y} + T_{yx} \cdot (-\Delta x) + T_{yy} \cdot (-\Delta y) \\ a_2 &= g_{2x} \cdot \sin \omega t - g_{2y} \cdot \cos \omega t \\ &= [g_{0x} + T_{xx} \cdot (-\Delta x) + T_{xy} \cdot (-\Delta y)] \cdot \sin \omega t - [g_{0y} + T_{yx} \cdot (-\Delta x) + T_{yy} \cdot (-\Delta y)] \cdot \cos \omega t \\ a_1 + a_2 &= R(T_{yy} - T_{xx}) \sin 2\omega t + 2RT_{xy} \cos 2\omega t \\ a_3 + a_4 &= -R(T_{yy} - T_{xx}) \sin 2\omega t - 2RT_{xy} \cos 2\omega t \\ (a_1 + a_2) - (a_3 + a_4) &= 2R(T_{yy} - T_{xx}) \sin 2\omega t + 4RT_{xy} \cos 2\omega t \end{aligned}$$

Figure 1 Working principle of gravity gradient sensor

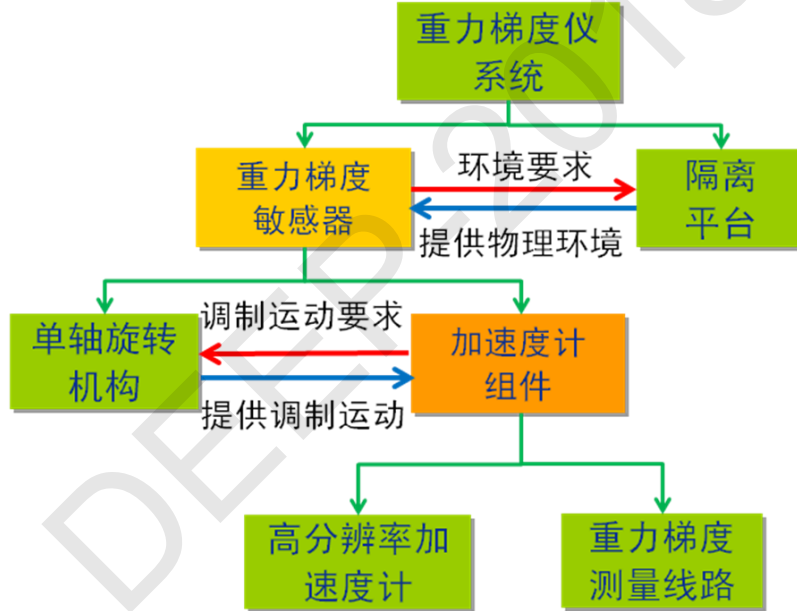


Figure 2. Block diagram of a gravity gradiometer

1.2 Research progress

1.2.1 High-resolution quartz flexible accelerometer

High-resolution quartz flexible accelerometer is the core component of gravity gradiometer. The current GGA-1B accelerometer is the first special accelerometer for gravity gradient measurement in China. It has the characteristics of high resolution, low noise and high consistency in performance. The accelerometer senses acceleration changes by measuring the mass of a quartz pendulum with a very low stiffness flexible joint. When there is acceleration along the input axis, the pendulum detection mass will deviate from the balance position according to Newton's second law of motion. The surface capacitance sensor

converts the deviation motion into an electrical signal. The servo circuit detects the electrical signal and generates a control current. The current enters the surface torque and acts on the permanent magnetic field to make the pendulum. The detection quality is back to zero, and the force balance current is proportional to the input acceleration.

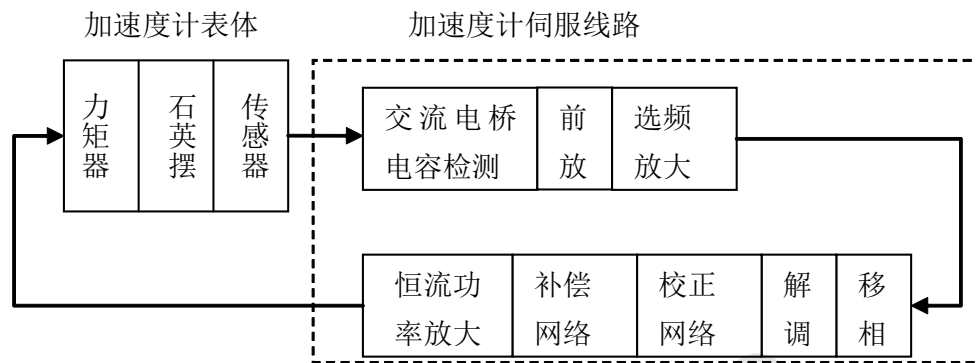


Figure 3 Working principle of high resolution accelerometer

The resolution of GGA-1B accelerometer is better than $5 \times 10^{-9}g$, reaching the best level of domestic quartz flexible accelerometer; the error of scale factor of paired accelerometer is less than 0.1% and the measuring range is greater than 1g; it has the mechanism and function of on-line adjustment of scale factor, filling the technical gap of domestic accelerometer.



Figure 4 High resolution quartz flexible accelerometer

2.2.2 Gravity gradient sensor

Gravity gradient sensor is used to measure gravity gradient tensor component by a set of high-resolution accelerometers and high-precision signal processing circuits mounted on a high-rigidity rotating body. The rotating modulation function realized by the shafting and rotating control system of precision rotating machinery provides necessary modulation conditions for gravity gradient measurement.

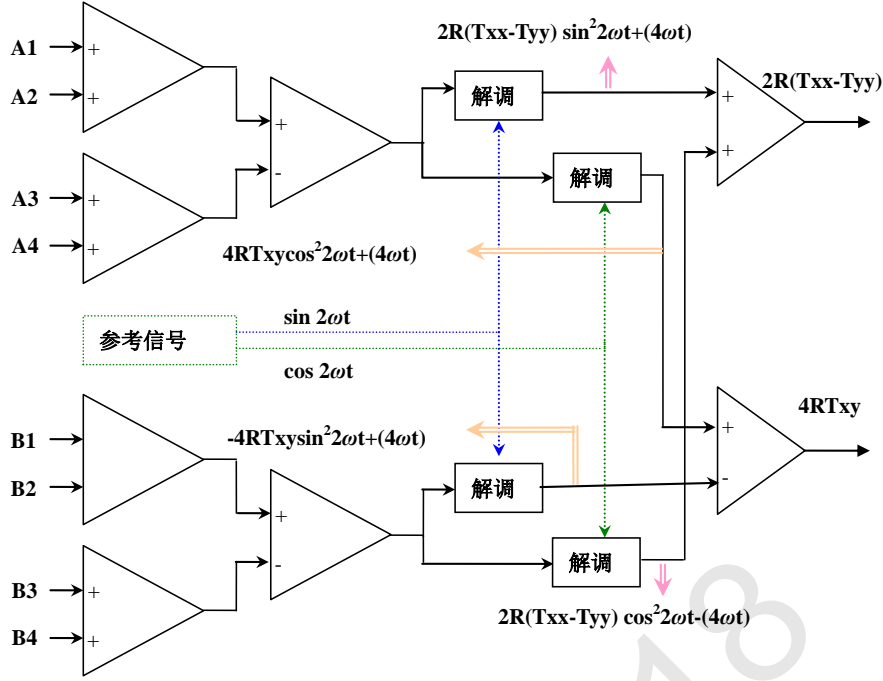


Figure 5 Working principle of gravity gradient sensor

The first set of miniaturized gravity gradient sensor in China has broken through high precision rotary modulation control, on-line real-time adjustment control of accelerometer scale factor, precise adjustment of accelerometer sensitive axis direction and detection center of mass, high rigidity shaft support design, high precision thin shell/frame integration design, thermal design of sensor chamber environment, The key technologies, such as high gain and high signal-to-noise ratio measurement circuit, narrowband demodulation and extraction of gradient signal, have reached 40E resolution level. The needle needs to dynamically measure the environment and complete the environmental sensitivity test of the gravity gradient sensor.

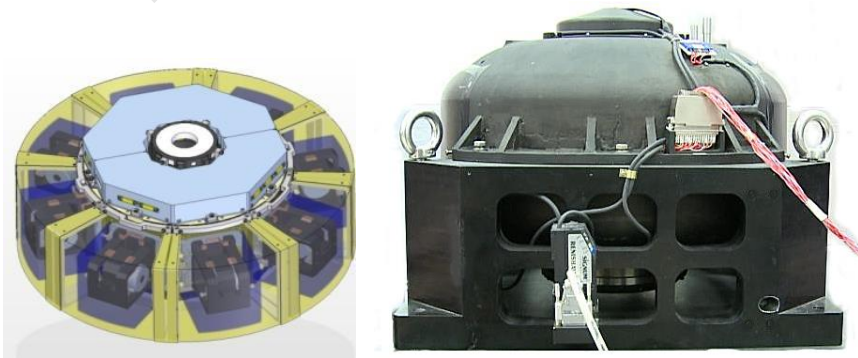


Figure 6 Gravity gradient sensor

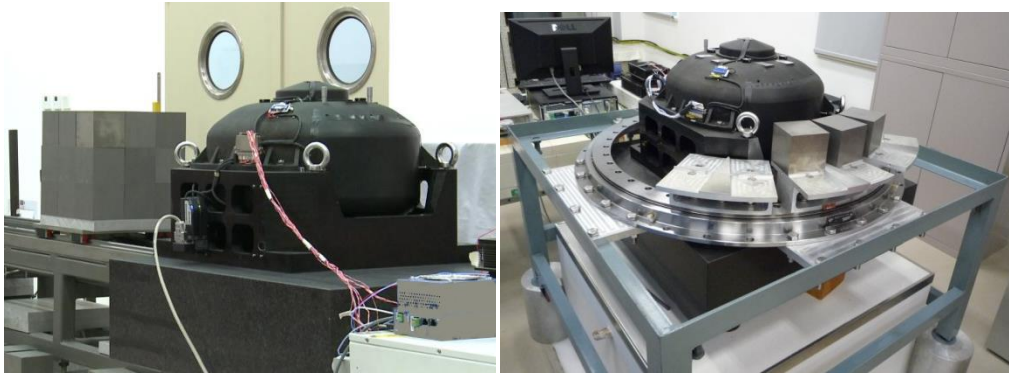


Figure 7 Horizontal excitation resolution test of gravity gradient sensor

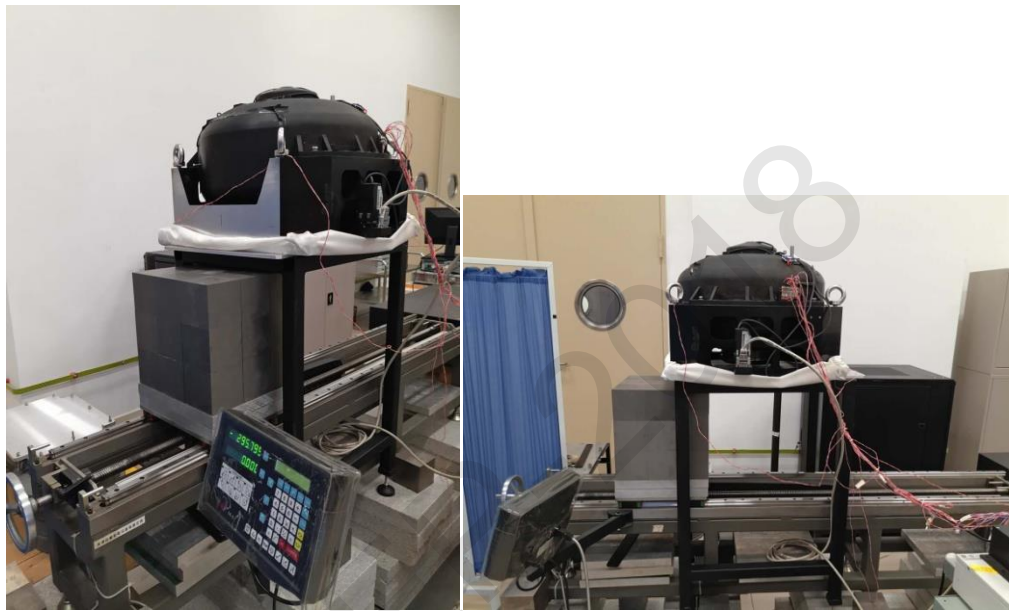


Figure 8 Vertical excitation resolution test of gravity gradient sensor



Figure 9 Vibration sensitivity test of gravity gradient sensor



Figure 10 Horizontal line motion sensitivity test of gravity gradient sensor



Figure 11 Sensitivity test of temperature gradient for gravity gradient sensor

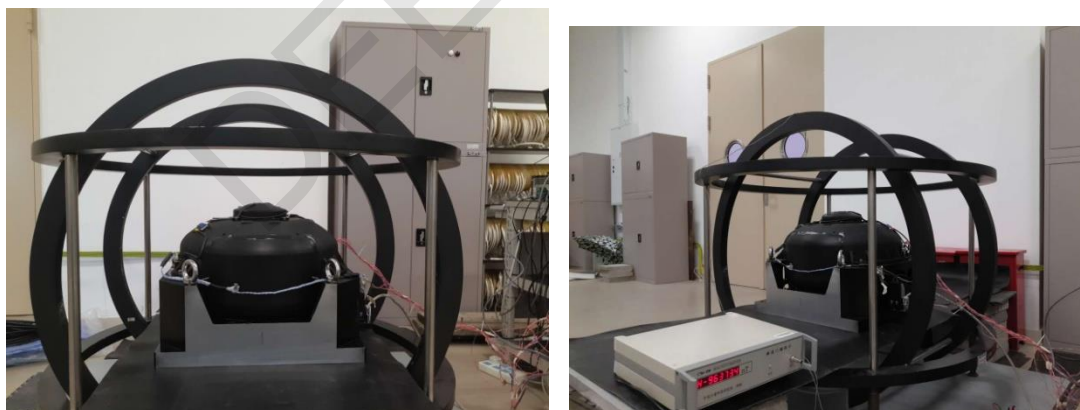


Figure 12 Magnetic field sensitivity test of gravity gradient sensor

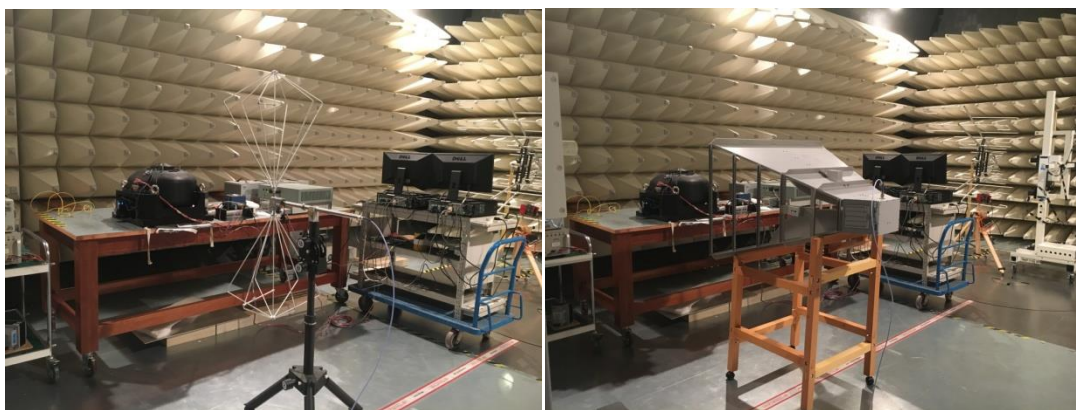


Figure 13 Electromagnetic compatibility test of gravity gradient sensor

1.2.3 Stabilized platform for gravity gradient measurement

Gravity gradient measurement stabilized platform is loaded with gravity gradient sensor to realize gravity gradient measurement on moving base under dynamic conditions. Its main function is to isolate the angular motion of the carrier under dynamic conditions and provide a stable gradient measuring coordinate system relative to the local geographic coordinate system for the gravity gradient sensor mounted on the platform. It provides a dynamic environment for gravity gradiometer sensors.

In order to improve the accuracy of gravity gradient measurement, a semi-analytical inertial stabilization platform with a fixed finger-to-north three-ring ring is adopted to stabilize the gravity gradient measurement platform. The stabilized platform adopts the structure of the outer axis platform, which is convenient for the arrangement, installation and disassembly of sensors, and can effectively reduce the overall volume of the stabilized platform.

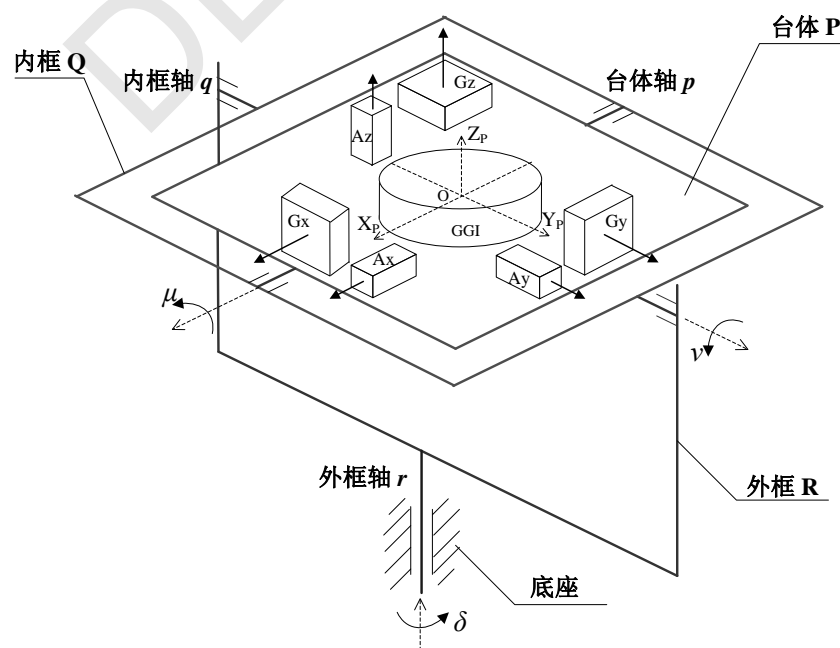


Figure 15 Structural layout of stabilized platform for gravity gradient measurement

Fiber optic gyroscope (FOG) is used to directly control the stabilization loop of gravity gradient measurement stabilized platform, which breaks through the control technology of large load, large size and high stiffness stabilized platform and achieves high precision angular motion isolation effect under high maneuvering conditions. Stabilized platform prototype completes swing, vehicle and aviation adaptability test.

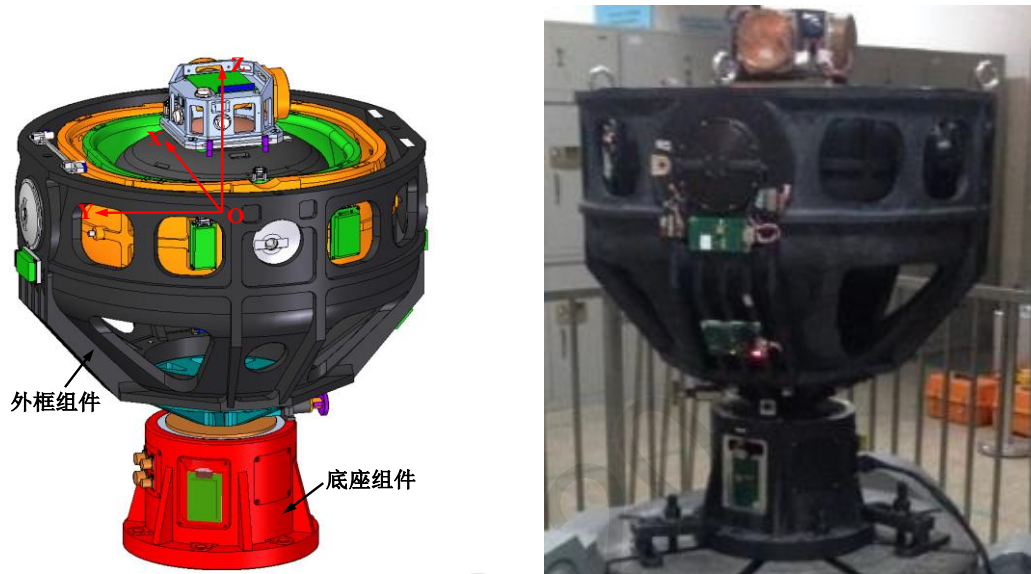


Figure 12 Stabilized platform for gravity gradient measurement

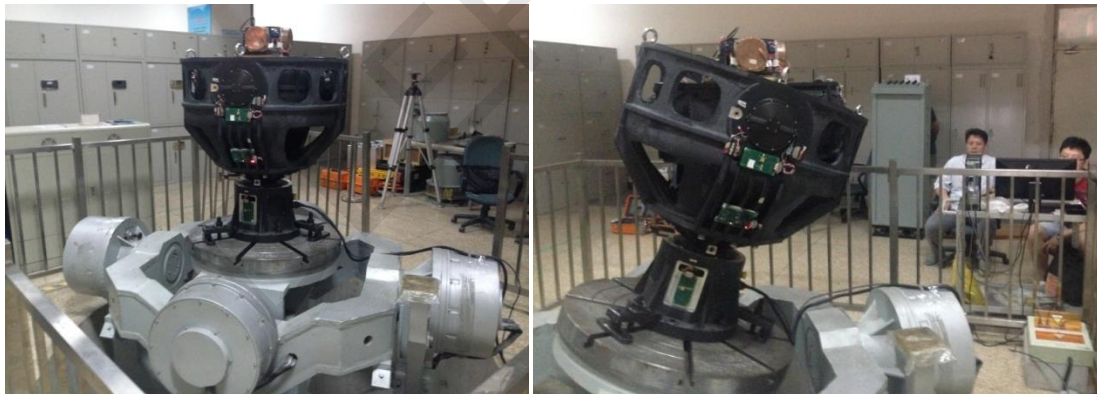


Figure 13 Shaking table test of stabilized platform for gravity gradient measurement



Figure 14 Vehicle test of gravity gradient stabilized platform



Figure 15 Aeronautical adaptability test of stabilized platform for gravity gradient measurement

1.2.4 System integration of gravity gradiometer



Figure 16 Integrated debugging of gravity gradient sensor and stabilized platform

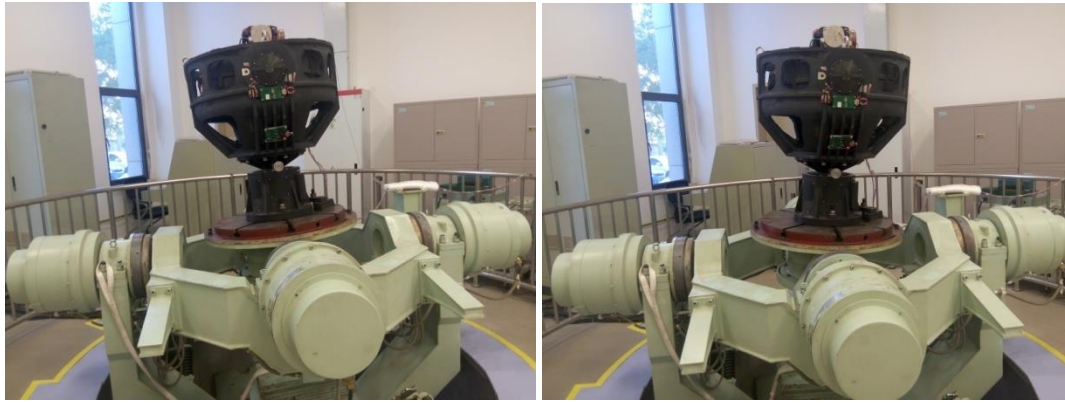


Figure 17 Rolling test of gravity gradiometer

2. Related work of ship gravity gradiometer test

2.1 Composition of gravity gradient measurement system based on ship

The ship-borne gravity gradient measurement with gravity gradiometer needs system integration based on the existing main instruments of gravity gradiometer to construct the main measuring equipment, and also needs integrated measuring auxiliary equipment.

(1) Measuring main equipment

The main equipment of gravity gradient measurement is the core equipment of gravity gradient measurement. It is composed of the main instrument of gravity gradient meter (including gravity gradient sensor and gravity gradient measurement stable platform), environment control device, power supply and distribution unit, comprehensive display console of measurement operation, measurement data acquisition and processing device, etc.

(2) Measuring auxiliary equipment

Measurement aids provide various carrier motion information for gravity gradient measurement operations, and are used for post-analysis and processing of gravity gradient measurement data, mainly including satellite navigation equipment and attitude and motion parameter measurement equipment.

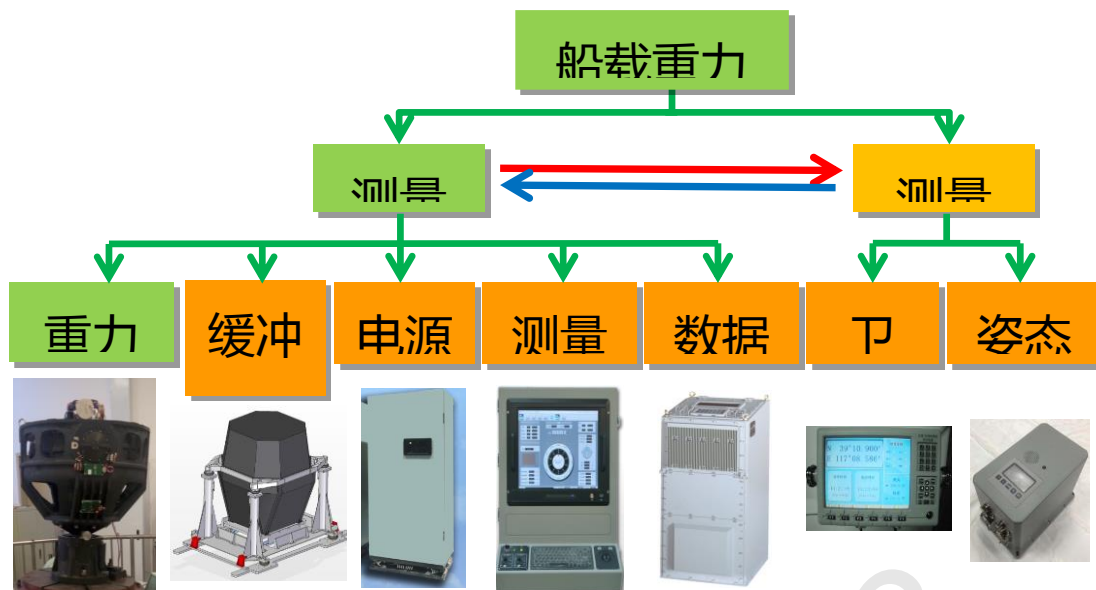


Figure 18 Composition of gravity gradient measurement system based on ship

2.2 Environmental adaptability of ship borne gravity gradiometer

Aiming at ship borne measurement, gravity gradiometer needs specific environmental protection measures:

(1) Reducing the Dynamic Interference of Linear Vibration to Gravity Gradient Output Signal under Navigation Conditions by Using Special Buffer and Shock Absorber;

(2) A special measuring environment control device is used to provide a stable temperature, humidity and atmospheric pressure environment for gravity gradient measurement, and to avoid the influence of various environmental disturbances on the accuracy of gravity gradient measurement.

According to the frequency spectrum analysis of ship vibration and the precision requirement of gravity gradient measurement, the damping index and main technical parameters of the buffer and shock absorber unit are determined.

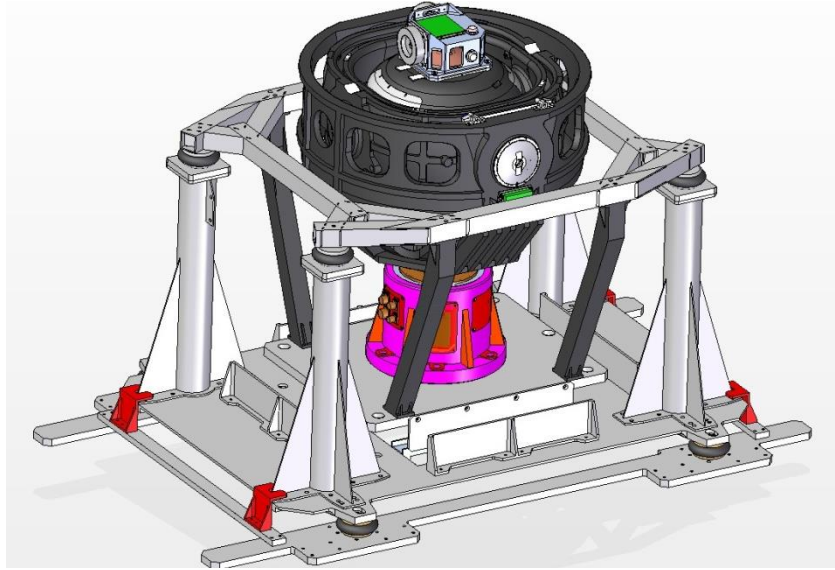


Figure 19 Design of cushioning and damping unit

The measuring environment control device adopts the closed-type gas-regulating environment control technology to realize the stable internal environment of gravity gradient measurement. The specific implementation scheme will be optimized in the integrated environmental control scheme and the external separate environmental control scheme of the thermostat.

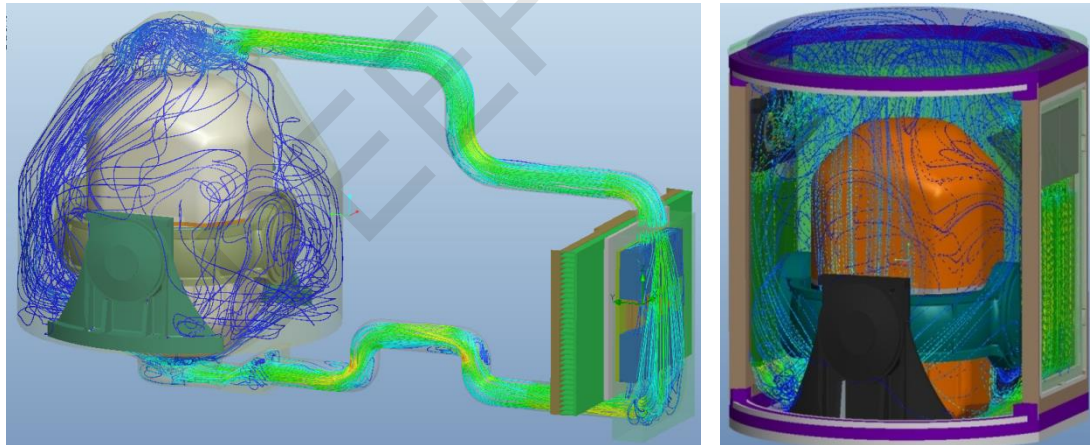


Figure 20 Design scheme of split and integral environmental control device

2.3 Installation technical requirements

- (1) The weight of the main equipment is less than 700kg, and the center of mass is higher than the bottom of the installation 750-800mm;
- (2) Dimensions of main equipment: 2.0m×1.4m×1.6m;
- (3) The main equipment enters the warehouse shape: (the equipment may disassemble into the cabin).1.8m×0.4m×1.5m;

- (4) Installation form: installation form and layout see attached drawings;
- (5) Lifting methods: dock to ship deck (mechanical hoisting); ship deck to installation compartment (preferably vertical into the cabin mechanical hoisting channel, or set up through the door hoisting slideway and lifting gear (load less than 300 kg); cabin interior (equipment installation axis above the installation of lifting slideway and lifting gear); rotary space range: $\Phi 2.5$ m.
- (6) Installation level: plus or minus 1 degrees;
- (7) Cabin area: not less than 15m^2 (width not less than 3m, height not less than 2.5m);
- (8) Installation equipment and other equipment distance requirements: cabin for the system independent cabin, equipment spacing see layout plan;
- (9) Power supply requirements: AC, 220V, current (average 0.7A, peak current 1A);
- (10) Equipment installation cabin environment requirements: ordinary air conditioning cabin, refrigeration load 1; cabin floor with high load bearing capacity, need to be placed in the center of mass of the equipment near the center of the ship swing.

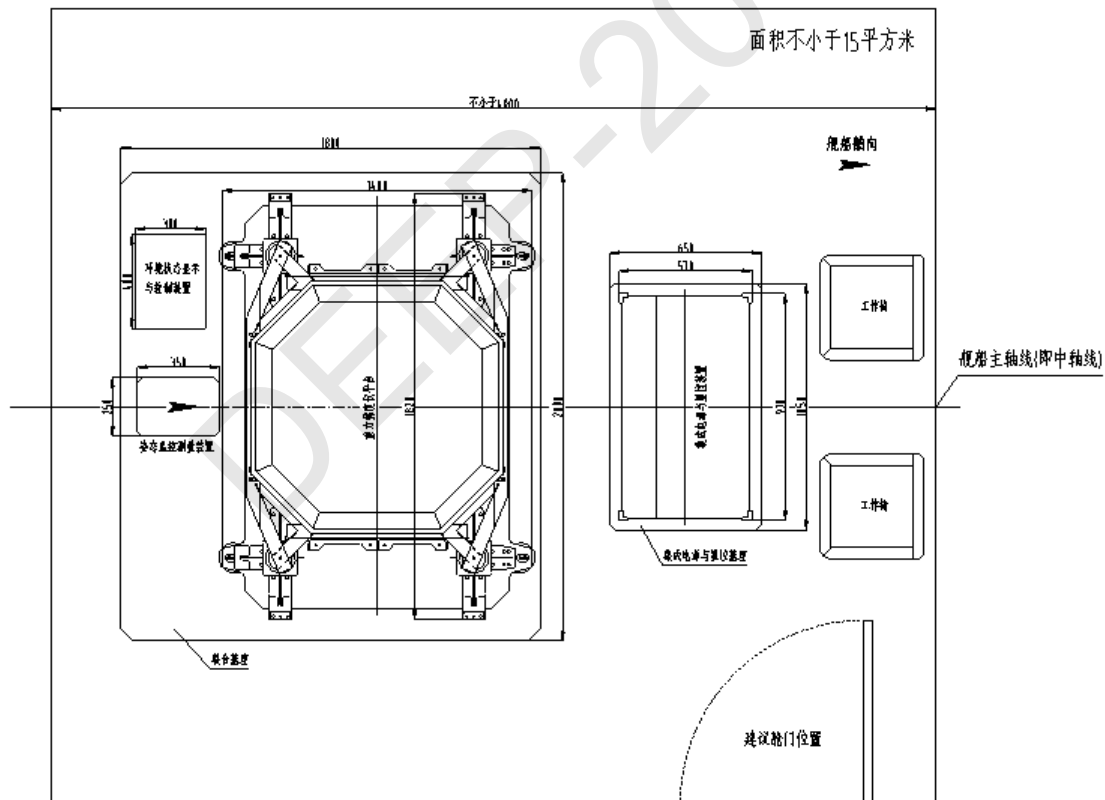


Figure 20 Installation layout diagram