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The Vibration Isolation Technologies of Load in Aviation and Navigation

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Abstract

Now, most of the instrument has become more precise, light-weight and portable so that the influence of the natural vibration and environmental noise confirms growing role in the instrument performance. The vibration source and the correspondent vibration isolation technologies were analyzed in the paper to provide theoretical reference for the vibration of the laser interference absolute gravimeter and theoretical guidance for the application of absolute gravimeter to the aviation and navigation.

Keywords: *aviation; navigation; vibration isolation; absolute gravimeter*

1. Introduction

As the instrument has become more precise, light-weight and portable, its performance is easily affected by natural vibration and environmental noise. For the airborne gravimetric system, high frequency disturbance produced from atmospheric turbulence would raise difficulty to navigation calculation, which as a result, takes its toll on navigation accuracy [1-3]. Studies on aeronautics and astronautics equipment failure show that 2/3 of the failure is related to vibration [4]. Ship, engines, propellers and wave would produce structural noise, air noise, water noise and the like, damaging the equipment system and causing it out of work [5].

Therefore, the aviation and the navigation industries are faced with new challenges on how to reduce vibration and noises in the gravimeter.

2. Vibration Source of Load in Aviation and Navigation

2.1. Vibration Source of Load in Aviation

2.1.1. Aero-Engine Body Vibration

Aero-engine body vibration is defined as aero-engines consisted of many freedom vibration systems respond to all kinds of vibration forces [6]. The aero-engine is very complicated, varying from each other in terms of mechanical structure which determines the vibration. The complicated mechanical structure would generate low frequency vibration (dozens of Hertz) or medium and high frequency vibration (from hundreds of Hertz to thousands of Hertz) during the operation of the aero-engine.

Influenced by structural design and manufacturing, the bearings of the aero-engine may cause natural vibration with front bearing waviness influencing the vibration the most. The contact and joint space between bearings present non-linear characteristic, making bearings and rotors subject to complex vibration. System response of bearings and rotors has several types of periodical vibration, quasi periodical vibration and non-periodical vibration [7]. Even if well manufactured, the

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rolling bearing may also have vibration. In the rotor system of the aero-engine, unbalanced force is another cause of vibration. Rotor imbalance is thought to be the primary reason for aero-engine body vibration.

2.1.2. Atmospheric Turbulence

During the flight, the aircraft may encounter wind shear at a low altitude, atmospheric turbulence at a middle and high altitude, and mountain stream, etc, causing spatial and time changes with regard to wind speed, wind direction and temperature. Atmospheric turbulence adds load to the place structure by activating the pneumatic surface and thus causes turbulence and vibration. High frequency atmospheric turbulence would interfere with the inner flow field of air inlet. When the frequency reached self-excited vibration frequency of supersonic inlet, which is 780Hz, there occurs acoustic resonance in the inlet [8].

2.2. Vibration Source of Load in Navigation

Equipment for civilian and military use on the ship would produce vibration as engines, propellers and wave lead to structural noise, air noise and water noise.

Ships usually have translational vibration vertical to sea wave or stormy wave. Their front part, left part and right part would rotate and vibration. Acceleration or braking in the forward direction can cause translational vibration, the frequency of which is as low as 0.1-3Hz [9, 10].

To conclude, there are three types of vibration source for warships in navigation:

1) Dynamic and mechanical noise: the engine of the warship works at 500-3000rpm. The vibration is as low as 8-500Hz. Given that the Dynamic and mechanical noise is at the low frequency level, it becomes the dominant noise for warships.

2) Propeller noise: rotation and vibration of the propeller blade is the main source of high frequency radiated noise of submarines.

3) Hydrodynamic noise: noises produced as the water flows through the surface and the appendage and produced from turbulent fluctuation pressure are in direct proportion to the ship speed to the power 6 [11].

In navigation, most load vibration is random, and usually is accompanied with resonance. Meanwhile, as vibration noises are random and complicated, they are easy to damage equipment, lower the accuracy. Thus, vibration is a great concern for gravimeter in navigation.

3. Vibration Isolation Measure for Vibration of Load

3.1. The Vibration Control Technology

Adopting vibration isolation measures are one of the common ways to control vibration. The vibration control technology can be divided into active control and passive control.

Active control (also called active vibration isolation) is defined as introducing a sub system of active control between the controlled object and the vibration source. The influenced of vibration source on the controlled object is controlled by energy input, according to the form of vibration of the object. The active vibration isolation system does not require external interference but can adapt to the working condition of the controlled object. It consumes energy while providing energy. Active control is the most ideal way to reduce vibration. However, it is costly, complicated and hard to realize. There are still problems in its application [12].

Passive control (also called passive vibration isolation) is defined as realizing vibration isolation without external energy supply. Such method is reliable, easy and operable. But the isolation effect is not as good as that of active control, nor is the passive control better adapt to the environment than active control [13].

In terms of mechanical structure, the vibration isolation technology consists of single-layer vibration isolation system, double-layer vibration isolation system and float raft vibration isolation system. The single-layer vibration isolation system has simple structure but poor isolation effect. It is not suggested to apply to low frequency vibration isolation. The double-layer vibration isolation system can achieve better isolation effect than the single-layer one. But it is more complicated in structure with a large volume. The float raft vibration isolation system draws merits from the double-layer system but is smaller in size.

3.2. Vibration Isolation Measures in Aviation and Navigation

At present, passive vibration isolation technology is the widest applied in aviation. Abundant products of this technology have performed well in the market, such as rubber vibration isolator, spring vibration isolator, steel wire rope vibration isolator, metallic rubber vibration isolator and the air spring vibration isolator, to name just a few. The metal vibration isolator can be further divided into metal spring in butterfly shape, plate spring and coil spring. It is adaptive to the working environment and has good isolation effect. Besides, it is easy to install and exchange. The steel wire rope vibration isolator can bear greater structural deformation and impact compared to other types, and it has high damping, heat-resistance, and is anti-aging. More importantly, the soft stiffness can equip it with hysteresis damping characteristic. The metallic rubber vibration isolator is special in that the shape of the metallic rubber can be processed according to actual need. Its strong plasticity makes it welcome in many fields. The air spring draws upon the non-linear restoring force produced when the air is compressed to realize vibration isolation. Its inherent frequency can reach below 1Hz, while the natural frequency of the rubber vibration isolation system is 5-7Hz. Thus, the air spring performs well in isolating low frequency vibration [14].

For equipment and devices, traditional vibration isolation system based on “discrete spectrum” has already been satisfying. But in aviation and navigation, aircrafts and ships are placed in a dynamic environment with random excitation, which results in that traditional vibration isolation devices fail to avoid resonance. With the advancement of science and technology, missiles and rockets pose higher requirement on navigation accuracy. This is another thing that traditional vibration isolation devices fail to achieve. At present, the viscoelastic damping vibration isolation device is applied to important equipment such as inertial platform in aviation. Though it has better isolation effect, the viscoelastic damping material is sensitive to temperature and poor in creep resistance. In other word, it is hard to preserve in the long term. The metal-rubber material is a replacement of the rubber material, and it can be used in severe environment. Compared to the rubber material, it is resistant to creep and can largely reduce the measurement error of the inertia system during the flight [15].

For ships, the vibration isolation technology has witnessed long-term development, from the original single-layer one to double-layer one and to float raft one. Currently, the float raft vibration isolation system is combined with the active control technology and plays an increasingly important role.

To some extent, the passive technology can control noises utter by the ship itself. But it doesn’t perform well in low frequency vibration, nor can it meet the requirement of the ship on broadband and frequency conversion. Traditional passive float raft is a typical passive vibration isolation technology. When the ship sails at a low speed, and when the excitation frequency of the equipment and devices is equal to or lower than the system resonance, the passive float raft vibration isolation device cannot isolate vibration anymore.

With the development of the vibration isolation technology, active isolation is taking up. However, due to the constraint of cost, the passive vibration isolation technology still takes the dominant. The rubber vibration isolation is widely applied to the power unit of ships and submarines [16-20].

4. Magnetic Suspension Vibration Isolation Technology

Study of magnetic suspension started when the permanent magnet material was born. As the magnetic field force of the magnetic suspension vibration isolator presents a non-linear relationship with two plates, the isolator can isolate vibration in a non-linear way.

The maglev supporting technology is contact-free, lubricated-free and not easy to wear a long service life, and the supporting parameters are adjustable (stiffness, damping) during operation. Applied to active vibration isolation system, it can make up for the "low-frequency failure" of the passive vibration isolation system and generate better isolation effect. Consequently, the active magnetic suspension vibration isolation technology is the main focus of relevant study.

Compared to other isolators, the magnetic suspension vibration isolator presents the following advantages [21]:

(1) There is no direct contact between parts, thus there is no mechanical friction and no need for lubrication. The service life is long.

(2) It has low requirement on the environment. It is working under high humidity and dust environment and regions with large day-and-night temperature.

(3) It has wide broadband and quick response to frequency. And the stiffness and the damping parameters are adjustable according to actual control.

(4) It consumes little energy and the calorific value is low. Only hysteresis and eddy current of the isolator causes some damage.

5. Errors of Gravimeter in Measurement Caused by Environment Vibration

Information about time and displacement of the faller captured by the interference fringe is a relative amount to the reference prism. Measurement errors are inevitable as environment vibration and the prism vibration caused by natural vibration of the faller control system in the falling process.

Suppose at T_0, T_1 and T_2, the displacement are X_0, X_1, X_2. It can be calculated that:

$$g = 2\frac{(X_2 - X_1)(T_1 - T_0) - (X_1 - X_0)(T_2 - T_0)}{(T_1 - T_0)(T_2 - T_0)(T_2 - T_1)}$$

Suppose:

$$\begin{cases} t_1 = T_1 - T_0 \\ t_2 = T_2 - T_0 \\ s_1 = X_1 - X_0 \\ s_2 = X_2 - X_0 \end{cases}$$

There is:

$$g = 2\frac{s_2 t_1 - s_1 t_2}{t_1 t_2 (t_2 - t_1)} \qquad \text{(4.1)}$$

If the reference prism emits a vibration signal in which the amplitude of is ε and the angular frequency is ω, errors at displacement X_0, X_1 and X_2 are:

$$\begin{cases} \varepsilon_0 = \varepsilon \sin(\varphi) \\ \varepsilon_1 = \varepsilon \sin(\omega t_1 + \varphi) = \varepsilon \sin(k_1 \omega t_2 + \varphi) \\ \varepsilon_3 = \varepsilon \sin(\omega t_2 + \varphi) \end{cases}$$

, where $k_1 = \frac{t_1}{t_2}$, φ is the initial phase of the vibration signal.

So (4.1) can be expressed as:

$$g = \frac{2}{t_2^2(1-k_1)}(s_2 - \frac{s_1}{k_1}) \quad \text{-----(4.2)}$$

Suppose $k_2 = \frac{s_1}{s_2}$, then (4.2) can be written as:

$$g = \frac{2s_2(k_1 - k_2)}{t_2^2 k_1 (1-k_1)} \quad \text{-----(4.3)}$$

From (4.3), the relative error of g caused by vibration signal is:

$$\frac{\Delta g}{g} = \frac{\varepsilon}{s_2(k_1 - k_2)}((1-k_1)\sin(\varphi) - \sin(k_1 \omega t_2 + \varphi + k_1 \sin(\omega t_2 + \varphi))) \quad \text{---- (4.4)}$$

From (4.4), it is known that the vibration frequency and amplitude do influence the measurement. And the vibration error varies from each other at different displacement. Moreover, as φ is random, the error of g is also random.

Suppose k1=0.5, and φ is temporarily a fixed constant. The amplitude is ε=0.1μm, t2=0.33s. At 0-30π (rad/s), the error curve can be calculated based on (4.4), as shown in Figure1. It can be seen that when the vibration amplitude of the reference prism is only 0.1μm, 0.33s after the faller falls generates the maximum measurement error, which is 100 micro gal. It is concluded that the vibration caused by the reference prism is relative large.

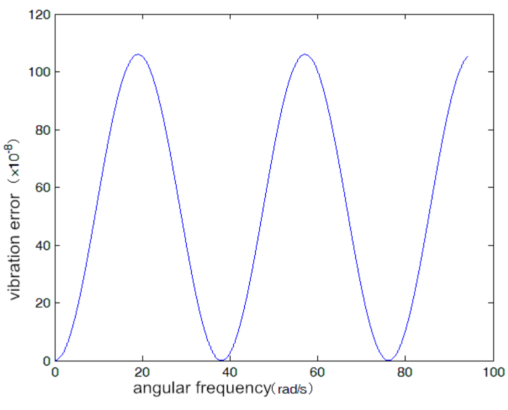

Figure 1. Measurement Error Caused by Vibration

On the basis of national gravity datum, the absolute gravimeter is adopted to conduct the measurement. Results show that if the gravitational acceleration of the faller is calculated by phase, and if it is compared with gravity reference, the deviation curve between the calculated gravity and the reference has a strong connection with the vibration signal of the reference prism recorded simultaneously, as shown in Figure2. It is thus concluded that the error is a response to the system's natural resonance.

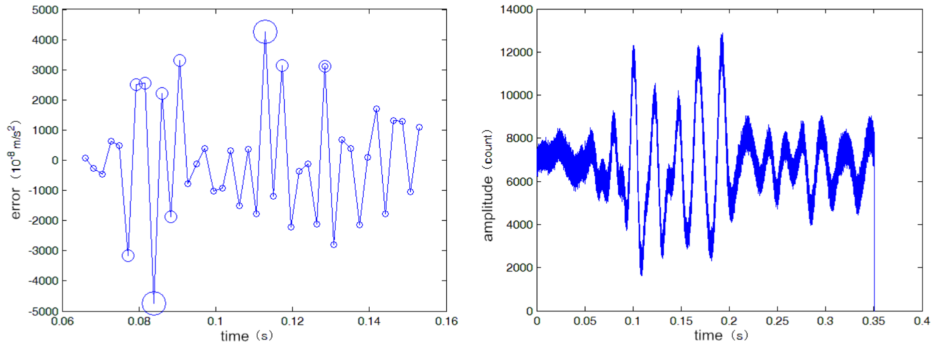

Figure 2. The Deviation Curve of the Gravitational Acceleration and the Vibration Waveform in the Falling Process

6. Conclusions

In this paper, vibration source of load in aviation and navigation and vibration isolation measures are analyzed. The passive vibration isolation device is simple in structure, easy to achieve, low cost and reliable. But the design parameters are hard to change. Theoretically speaking, the isolation effect is good only when it is applied to equipment whose vibration is $\sqrt{2}$ times of the install frequency. So, it is not suitable for low frequency vibration isolation. In comparison, the active vibration isolation device can achieve satisfying isolation effect on low frequency vibration and its parameters are adjustable. But due to a complicated structure and the requirement of energy input, the active vibration isolation device is usually applied to isolate low frequency vibration.

Among existing isolation measures, the passive vibration isolation technology is the most widely used. The active vibration isolation technology and the active magnetic suspension vibration isolation technology are two hot issues concerning structural control. Yet they are not applied to ships. In the aviation field, the metallic rubber isolator is the dominant device while in the navigation field, the rubber isolator is superior to others.

On the land, vibration disturbance of the absolute gravimeter by the laser mainly presents high frequency. Thus, the passive vibration isolation device is quite suitable. In aviation and navigation, the form of vibration disturbance needs further experiment and design should be based on existing isolators.

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