An Online Calibration and Detection Method for Inertial Equipment on Aircraft

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Abstract. At present, the calibration and detection for inertial equipment on aircraft generally need to disassemble the inertial equipment from the aircraft, and it is inconvenient to use this method to maintain the inertial equipment. An online calibration and detection method is proposed in the paper, which is able to obtain the detection indexes by combining the vertical and rotary motion of the launching vehicle. The indexes contain the zero drift indexes, the scale factor nonlinear indexes and the attitude angle error indexes of the gyro and accelerometer. By judging if these indexes are within the threshold range of requirements, we can determine whether the inertial equipment perform well. Using the designed limit index as the calibration parameter, the simulation experiment of shooting is carried out to verify the effectiveness of the designed method. The simulation results show that the miss distance meets the design requirements within the limit index range. The designed algorithm can directly detect the inertial equipment online, avoiding the repeated disassembly and assembly problems caused by the traditional detection methods, and reducing the test and maintenance costs.

1. Introduction
With the continuous development of global science and technology, the technical level of national defense and military industry in various countries is also constantly improving, and the demand for the ability of weapon equipment to cope with various working conditions and environments is also increasing. Vehicle mounted rocket launching system is an important branch of rocket weapon system, which has the advantages of strong surprise attack ability, violent, long range, strong maneuverability and fast response [1]. It is often used in tactical raids, destroying the enemy's deep targets and so on. It is an indispensable suppression and support weapon for land warfare platforms in modern warfare [2]. In order to ensure that the rocket weapon can attack the target accurately, the navigation system with inertial measurement devices (gyroscope, accelerometer, etc.) as the core is widely used [3]. The test accuracy performance of the navigation system has a crucial impact on the performance of the combat effectiveness, and has become a key component of the vehicle rocket launch system.

However, in the battlefield with complex environment, the inertial measurement devices are easily affected by road bumps, vibrations, explosions and other factors, which may cause the navigation system positioning misalignment [4]; in addition, there is a parameter validity period of the inertial equipment, and long-term storage may lead to a large measurement deviation of the inertial equipment. Therefore, it is very important to test the performance of vehicle inertial equipment. Li Guodong [5], Crispoltoni [6], Castaldi [7], and so on [8, 9] detected the IMU fault by building platform or model for simulation. However, these are only related to the level of algorithm research, not applied to the actual equipment. At present, the traditional method to detect the loaded inertial equipment is to remove the
equipment from the bomb, and then detect it off-line through the special detection equipment. For example, Tang Xiaqing [10] designed a general inspection and maintenance platform to detect the vehicle inertial navigation system offline; Ren Xiuying [11] designed a virtual detector of the inertial navigation device using industrial standard computer or workstation with powerful application software, low-cost hardware and driving software for the fault detection of the inertial navigation device. However, the disassembly and reinstallation of inertial equipment not only increases a lot of work and preparation time, but also is not conducive to dealing with the transient of the battlefield, and has hidden dangers to the reliability of products. Some other methods are to use special large-scale detection equipment to detect the whole projectile, but this method requires high precision of detection equipment, which improves the complexity and cost of online detection.

To improve the adaptability to the changeable environment of the battlefield, increase the flexibility of the equipment, reduce the detection of finished products, and realize online detection, a new on-line parameter detection strategy is presented for vehicle inertial equipment. The proposed algorithm uses the information interaction between the inertial equipment and the launching vehicle, uses the simple vertical rotation action of the launching vehicle and the measurement results of the inertial equipment to calculate the zero drift index of the gyro and the stability index of the accelerometer, so as to check whether the parameters of the inertial equipment are qualified. The method not only avoids the potential risks caused by repeated disassembly and assembly of inertial equipment due to the test requirements, reduces the maintenance cost, but also can detect the inertial equipment online in various environments to ensure the normal operation of the equipment.

2. Online detection strategy of vehicle inertial equipment

2.1. Overall scheme of detection strategy

Based on the analysis of the working principle and basic characteristics of the inertial navigation system, the cooperation test action of the launch vehicle is designed reasonably. From the perspective of convenient realization, adaptability to various environments and representative test results, combined with the actual needs of the combat forces, the reasonable test strategy is determined.

![Flow chart of on-line detection strategy for vehicle inertial equipment](image_url)

**Figure 1.** Flow chart of on-line detection strategy for vehicle inertial equipment
The specific flow of the detection strategy is shown in figure 1. The power supply of the missile is used and the engine is shut down. The inertial navigation equipment can read continuously and calculate the zero drift and stability index of gyro and accelerometer. Then use the vertical rotation action of launching vehicle and make the inertial navigation equipment read continuously to calculate the scale factor index of gyro and accelerometer. The performance of z-axis accelerometer is tested by the difference between the maximum value of z-axis acceleration after erecting and the average value of z-axis acceleration before erecting.

2.2. Workflow of launch vehicle
Because the whole testing process is in need of the cooperation of the launching vehicle, to ensure the validity and representativeness of the collected data, a set of reasonable operation process of the launching vehicle needs to be designed. This process should not only ensure the collection of complete test data, but also be easy to operate and realize.

First, it is necessary to find the north and level the reflecting vehicle to provide a relatively horizontal test platform, and to provide initial data for the inertial equipment. Then turn off the engine to ensure that the platform provided by the launching vehicle is relatively stable without major disturbance. Start the inertial equipment to enter the navigation state, and after it is stable, communicate with the launching vehicle twice to record the navigation data, 10 frames of data each time, with an interval of 30s. Then, start the engine for vertical rotation. When the vertical rotation is in place, turn off the engine to ensure the relative stability of the launching vehicle, communicate the inertial equipment with the launching vehicle, and record 10 frames of navigation data. Then, start the engine and control the launch vehicle to return to the initial horizontal position. Thereafter, shut down the engine, carry out the communication between the inertial equipment and the launch vehicle, and record 10 frames of navigation data. Finally, wait for the calculation to be completed, the launch vehicle exits the levelling state, and the engine is shut down to end the detection process. The specific process is shown in figure 2.

2.3. Calculation of the test index
2.3.1. Calculation of the gyro zero drift index. The two sets of angular velocity values recorded 30 seconds before the launch vehicle vertical rotation are used as input values, and the angles \( \theta_{k1} \) and \( \theta_{k2} \) (degree) of the two times is obtained through integral calculation. Then calculate the gyro zero drift (\(^\circ/\text{h}\)) as follows:

\[
B_{ok} = \frac{\theta_{k2} - \theta_{k1}}{30} \times 3600
\]

where \( B_{ok} \) represents the gyro zero drift, and \( k = x, y, z \) represents three angles (rolling angle, yaw angle and pitch angle).

2.3.2. Calculation of the accelerometer zero position stability index. Take the measurement results \( a_{ik} \) (g) of two groups of accelerometers as input, which is recorded 30 seconds before the launch vehicle rotates vertically, and calculate the average value \( \bar{a}_k \) (g) of the two groups of results. Then calculate the standard deviation (mg) of the two groups of data as follows:
\[ B_{ak} = 1000 \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (a_k - \bar{a}_k)^2} \]  \hspace{1cm} (2)

where \( B_{ak} \) represents the accelerometer zero drift, \( k = x, y, z \) represents three axis directions, and \( n \) represents the number of two sets of data.

2.3.3. **Calculation of the gyro scale factor index.** The gyro scale factor index is expressed by the attitude angle error (°) of the launching vehicle under the launching coordinate system after vertical rotation. It is obtained by calculating the difference between the actual value and the theoretical value of the attitude angle under the launching coordinate system after vertical rotation. The specific calculation formula is as follows:

\[ \Delta \theta_k = \theta_{k3} - \theta_{k1} - \hat{\theta}_{k0} \]  \hspace{1cm} (3)

where \( \Delta \theta_k \) is the attitude angle error, \( \theta_{k3} \) is the attitude angle obtained by the recorded gyro output after erecting, \( \theta_{k1} \) is the attitude angle obtained by the first recorded gyro output before erecting, \( \hat{\theta}_{k0} \) is the theoretical value of attitude angle, and \( k = x, y, z \) is three angles (rolling angle, yaw angle and pitch angle).

**Remark 1:** The theoretical attitude angle in the launch coordinate system is calculated as follows:

First, the attitude transformation matrix is calculated as:

\[
T = \begin{bmatrix}
1 & 0 & 0 & \cos(\phi_0) & \sin(\phi_0) & 0 & \cos(\psi_0) & 0 & -\sin(\psi_0) \\
0 & \cos(\theta_{\phi0}^e) & \sin(\theta_{\phi0}^e) & -\sin(\phi_0) & \cos(\phi_0) & 0 & 0 & 1 & 0 \\
0 & -\sin(\theta_{\phi0}^e) & \cos(\theta_{\phi0}^e) & 0 & 0 & 1 & \sin(\psi_0) & 0 & \cos(\psi_0)
\end{bmatrix}
\]  \hspace{1cm} (4)

where \( \theta_{\phi0}^e \) is the left and right non-levelness of the vehicle, \( \phi_0 = 30^\circ - \theta_{\phi1}^e \) is the erecting angle of the vehicle, \( \theta_{\phi1}^e \) is the front and rear non-levelness of the vehicle, and \( \psi_0 \) is the turning angle of the vehicle.

Then, the theoretical attitude angle is calculated by the attitude transformation matrix as follows:

\[
\begin{align*}
\text{rolling angle} & : \hat{\theta}_{\phi0} = \arctan(T_{23}/T_{33}) \\
\text{yaw angle} & : \hat{\theta}_{\psi0} = \arcsin(-T_{13}) \\
\text{pitch angle} & : \hat{\theta}_{\phi0} = \arctan(T_{12}/T_{11})
\end{align*}
\]  \hspace{1cm} (5)

2.3.4. **Calculation of the gyro scale factor auxiliary index.** The gyro scale factor auxiliary index is the consistency index of attitude angle after launching the vertical rotation and returning to the horizontal position and before the vertical rotation, which is expressed by the absolute value (°) of the difference between the two groups of attitude angles. The specific calculation method is as follows:

\[ \hat{\theta}_{ak} = |\theta_{k4} - \theta_{k1}| \]  \hspace{1cm} (6)

where \( \hat{\theta}_{ak} \) is the absolute value of attitude angle difference, \( \theta_{k4} \) is the attitude angle obtained by the recorded gyro output after erecting and \( k = x, y, z \) is three angles (rolling angle, yaw angle and pitch angle).

2.3.5. **Calculation of the accelerometer scale factor index.** The accelerometer scale factor index is expressed by the difference between the calculated value by the pitch and roll angle of the accelerometer output and the theoretical value, that is, it is indirectly determined by the attitude angle calculated by the accelerometer. The specific formula is as follows:
\[
\begin{align*}
\Delta \theta^a_z &= \theta^a_z - \theta_{z0} = \arctan(\overline{a}_x / \overline{a}_y) - \theta_{z0} \\
\Delta \theta^b_z &= \theta^b_z - \theta_{z0} = \arctan(-\overline{a}_x / \overline{a}_y) - \theta_{z0}
\end{align*}
\]  

(7)

where \(\overline{a}_x, \overline{a}_y, \overline{a}_z\) represent the average value of accelerometer 3-axis output after vertical rotation, \(\theta^a_z\) is the pitch angle calculated by the accelerometer, \(\theta^b_z\) is the roll angle calculated by the accelerometer, \(\theta_{z0}\) is the theoretical vertical value, and \(\theta_{z0}\) is the roll angle caused by the coupling of left and right non-levelness and the vertical rotation.

2.3.6. Calculation of the Z-direction accelerometer performance index. The Z-direction accelerometer performance index is represented by the absolute value (mg) of the difference between the maximum value (g) of all Z-direction accelerometer output recorded in the whole test process and the first recorded accelerometer output (g) before erecting. The specific formula is as follows:

\[
\Delta a_z = |a^z_{\text{max}} - \overline{a}_z| \times 1000
\]  

(8)

where \(a^z_{\text{max}}\) is the maximum value of Z-direction accelerometer output, \(\overline{a}_z\) is the accelerometer output value recorded in the first time before erecting, and \(\Delta a_z\) is the absolute value of difference.

Remark 2: Because the launch vehicle cannot directly make reference action for the performance detection of z-axis accelerometer from the system point of view, it is necessary to design indicators to determine the performance of z-axis accelerometer.

2.3.7. Calculation of the accelerometer output interpretation index. The accelerometer output interpretation index is expressed by the absolute value (m/s²) of the difference between the local gravity acceleration calculated by the accelerometer and the theoretical value of the local gravity acceleration. The specific calculation method is as follows:

First, calculate the theoretical value of local acceleration of gravity:

\[
g = 9.780325 \left[ 1 + 0.00530240 \sin^2(\text{lat}1) - 0.00000582 \sin^2(2 \cdot \text{lat}1) \right] \frac{R_e^2}{(R_e + h1)^2}
\]  

(9)

where \([\text{lat}1, \text{lon}1, h1]\) are the latitude, longitude and height of the actual geographical location, \(R_e\) is the semimajor axis of the earth in WGS-84 coordinate system.

Then, calculate the absolute value of the difference (mg):

\[
\Delta g = \left| g - \sqrt{\overline{a}_x^2 + \overline{a}_y^2 + \overline{a}_z^2} \cdot g_0 \right| \times 1000 / g_0
\]  

(10)

where \(g_0 = 9.80665\text{ (m/s}^2\text{)}\), \(\overline{a}_x, \overline{a}_y, \overline{a}_z\) are the average value of three-axis output of two groups of accelerometers before erecting, and \(\Delta g\) is the absolute value of difference.

Finally, according to the requirements of design and application, the corresponding threshold range is set for the interpretation of each detection index. By judging whether the index value is within the range, the performance of the inertial equipment is determined.

3. Simulation

To verify the designed index and strategy can be used to detect the state of inertial equipment accurately, flight simulation test is carried out by using the limit index set by the inertial equipment of launch vehicle. The limit indexes are listed in table 1.
Table 1. Limit indexes of inertial equipment of launch vehicle

|          | Limit indexes                                      | Values |
|----------|---------------------------------------------------|--------|
| Gyro     | Limit nonlinear index of scale factor (°)         | 2.5    |
|          | Limit index of zero drift (°/h)                   | 60     |
|          | Limit nonlinear index of scale factor (mg)        | 1      |
| Accelerometer | Limit index of x-axis and y-axis deviation stability (mg) | 3      |
|          | Limit index of z-axis limiting amplitude (mg)      | 40     |

The range of the flight simulation is 200km, and the random shooting tests of 1000 trajectories are carried out under three conditions: no lateral maneuvering (the result of which is shown in figure 3), 5 km left lateral maneuvering (the result of which is shown in figure 4) and 5 km right lateral maneuvering (the result of which is shown in figure 5).

Figure 3. Results of target shooting without transverse deviation

Figure 4. Results of target shooting with 5 km left lateral maneuver

Figure 5. Results of target shooting with 5 km right lateral maneuver

According to the simulation results, the miss distance is within 30m, which meets the requirements of design and application. Because the simulation result is obtained under the limit value of the index, when the actual index is less than the limit index, the shooting result must be within the required miss distance 30 m. The simulation results show that the designed detection strategy can effectively detect the performance of the inertial equipment of the launch vehicle.

4. Conclusion

This paper mainly studies the on-line detection of the inertial equipment on the launch vehicle, and designs a new detection strategy in view of the limitations of the high cost of the whole missile detection equipment, the difficulty of implementation, and the potential risk of disassembly and assembly of the missile. The proposed detection method uses the launch vehicle equipped with the weapon equipment to perform several simple operations, and with the measurement results of the inertial equipment, to calculate several necessary indexes which are used to detect the performance of
the inertial equipment. This method not only avoids the risk of repeated disassembly and assembly, but also replaces the whole bullet detection of large equipment, reduces the maintenance cost. Moreover, it ensures the flexibility and mobility in the complex battlefield environment. In addition, the proposed Z-direction accelerometer detection method solves the problem that the launch vehicle system cannot provide a reference for Z-direction accelerometer verification from a systematic point of view. Finally, through the simulation, it is verified that the designed detection method can effectively detect the performance of inertial equipment.

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