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Research on Attitude Measurement for Ballistic Correction Rocket

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Abstract

Ballistic correction rocket is a kind of smart ammunition which can attach aims exactly. Based on domestic and foreign literature, the technology of flight attitude measurement technology was summarized. The process of the research includes independently inertial measurement unit and inertial navigation system. The previous stage is the measurement technology only depend on a navigation equipment, such as accelerometer, Gyro or electromagnetic sensors etc, the latter means combinations of several measurement units, on the basis of complementary advantages in performance to improve computing accuracy each other. Based on the measurement technology was analyzed and compared, configuration, merit and demerits of multi accelerometer were discussed in detail. The paper prospected the future development of this technology finally.

Keywords: *ballistic correction rocket, inertial navigation system, attitude measurement, inertial measurement unit*

1. Introduction

The parameter of air target flight attitude embraced variation of roll velocity, pitch angle, yaw angular etc, which played an important role in trajectory correction and controlling the attitude. Domestic and foreign research on air target attitude testing technology is very extensive, developing from the earliest use of Gyro or accelerometer measuring angular acceleration to now research technique on various inertial navigation systems. The article presented a configuration and the computation algorithm analysis on the process of technology, independently inertial measurement unit and inertial navigation system. The problem need to be resolved of the future development was presented finally.

2. Independently Inertial Measurement Unit

In the inertial navigation system, Gyro was used initially to measure the flight attitude angle, it can also measure the flight attitude displacement of pitch angle, yaw angular and roll angle. When air targets were MMW-RCTCM and its performance such as volume, speed, acceleration and impact resistance etc had a high requirement, it required that Gyro had these characteristics such as small volume, light weight, strong impact resistance and wide range etc. With the development of the technology of Gyro, it had developed from the 18th century Rigid Rotor Gyro to Liquid Floated Gyro, Gas Lubricated Gyro, DTG (Dynamically Tuned Gyro), currently Electrostatic Gyro, Laser Gyro, Fiber Optic Gyro and Hemispherical Resonator Gyro [1-3] were widely used. Among them, the Fiber Optic Gyro development is the most quickly, and from the future development prospects, it is the main direction of the future development. Although the development of the gyroscope is more than one hundred years of history, to meet the needs of development of future military, we need to continue to reduce the volume, quality and cost, to continue to improve the reliability, stability and durability.

Due to the traditional mechanical gyro was made based on angular momentum conservation principle, which has complex structures and larger volume, new gyro such as Laser Gyro, Fiber Optic Gyro and micromechanical gyroscope have higher cost, poorer impact resistance, inherent zero-drift and the error is accumulated gradually with change of time, then affecting the precision of resolving of system attitude angle. So engineers and technicians

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researched and used accelerometer instead of Gyro, and solved the angular velocity of flight carrier from specific force measured by accelerometer. The research showed that Non-gyro Strap-down Inertial Navigation System was suitable for inertial guidance with large dynamic range and short navigation time, and had advantages of low cost, low power consumption, long life, high reliability, anti-high overload. With the emergence of high precision accelerometer and filter technique development, accelerometer can achieve better navigation precision.

The technology of using the accelerometer instead of Gyro to measure flight body attitude developed for almost 50 years. As early as in 1962, Victor B.Corey discussed the principle of the use of linear accelerometers measuring the angular acceleration, put forward a simple presentation of an accelerometer [4]. In the year of 1965, V.Krishnan discussed the mathematical principles of measuring angular velocity and linear acceleration of body by linear accelerometer installed in the evenness rotating disk [5]. Alfred R.Schuler then in 1967 came up with the idea of a linear accelerometer measuring the rotational motion of the object, and a variety of accelerometer configuration [6]. A.J.Padgaonkar in 1975 presented the method of calculating angular acceleration and linear acceleration of body by using mechanics choreography of nine-accelerometer [7]. In 1982, ShmuelJ.Merhav further studied non-gyro inertial measurement unit consisted of rotating or vibrating accelerometer triples, and discussed the method of isolating angular velocity and linear acceleration from accelerometer output signal[8].In the year of 1991, Algrain elaborated that at least 6 accelerometers could measure angular acceleration and linear acceleration of the object. Chen in 1994 discussed a novel design of using 6 accelerometers to measure attitude. In 1999, Lee gave an algorithm of using 6 accelerometers to measure rotation movement of an object.And the same year, Xie Chun-si and others offered an idea, that was using multiple laser tracker to determine the missile position, posture and rolling rate,Wang Guang-long and others in BIT (Beijing Institute of Technology) also proposed that to use Earth Magnetic Field Sensor to measure projectile attitude. In 2000, Thomas Harkins and others proposed the method of determining attitude by phase information of Magnetic Sensors output when zero crossing. In 2001, Chin-Woo proposed a sufficient condition to determine weather the accelerometer allocation scheme was feasible. In 2002, Lee improved filtering algorithm. In the year of 2003, Gui Yan-ning and others put forward and realized Solar Aspect Angle telemetering system. In 2004, Zhang Wei-hua and others put forward the detection of rocket rotation angle by Utilizing Geomagnetic Induction Coil. In 2009, Li Ding and others put forward a method of measuring attitude by the combination of two Magnetic Sensors.

Using laser to measure missile position and attitude was suitable for midcourse guidance and terminal correction, as a result of ground-based laser device, thus limiting the missile's flight distance; the method of determining attitude by phase information of Magnetic Sensors output when zero crossing could only figure out one information of pitch angle when projectile body span for a round, and the result was binary, which need to estimate the pitch angle with the help of one of the Magnetic Sensors. The method of using Earth Magnetic Field Sensor to measure projectile attitude had been applied for some type of missile attitude measurement, the results of measurement met the requirements, the testing system had simple structure, strong impact resistance, signal detection circuit with high sensitivity, stable work, the main design ideas of which was that three coordinate axes of Earth Magnetic Field Sensor were fixedly connected in projectile coordinate, which was used to measure the axial earth magnetic field component, and then measure one of pitch angle, yaw angular and roll angle through the auxiliary method to determine attitude angle of the flight body coordinate system in the geodetic coordinate system, but the method need auxiliary means, essentially still could not completely rely on earth magnetic realized the independent gesture recognition. The digital solar aspect angle telemetering system designed by the measurement fundamentals of solar aspect angle did a range dynamic test, which could withstand maximum 18000g launching load, and which was the domestic first one that successfully applied the principle of solar aspect angle to finish a the projectile attitude measurement test under the condition of the high value g, the test showed that the method could be used to measure spin-stabilized projectile attitude in flight, but only the case of sufficient sunlight during the day and with a larger applied limitations. The idea of putting the magnetic induction coils into the rockets proposed by Zhang Wei-hua and others, which used the rocket rotation to make induction coils to incise the magnetic line and produce electromotive, and the idea that the change of induction coils electromotive could reflect the situation of rocket rotation, easily achieve the test system of simple combination, low cost, high reliability and good real-time. But during the measuring process, blind zone appeared easily. Because of the speed of change of rockets rotation angle in flight was fast, once the blind zone appeared, measurement accuracy would be affected, furthermore, induction coils electromotive was concerned with rotational frequency, so the method did not applied to the low frequency rotation projectile. The method of using computation algorithm of ratio of extreme value of two magnetic sensors could achieve the high-speed projectile body attitude measurement, simulation result showed high precision, and characteristics of all-weather, day and night suing. Whether it could be applied in practice, it needed more comprehensive validation.

In recent years, research of multi-accelerometer combination design is very extensive, design of six-accelerometer, nine-accelerometer, ten-accelerometer, seven-accelerometer single gyroscope, eight-accelerometer and twelve-accelerometer etc come out, the following are describe in detail for different combinations of configurations and computation algorithm.

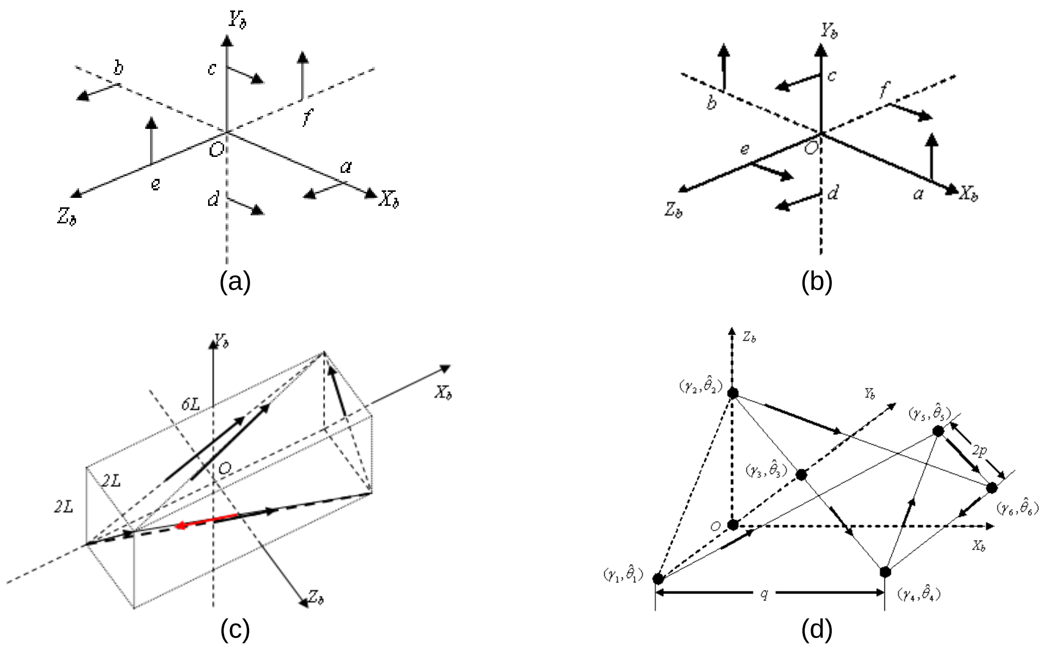
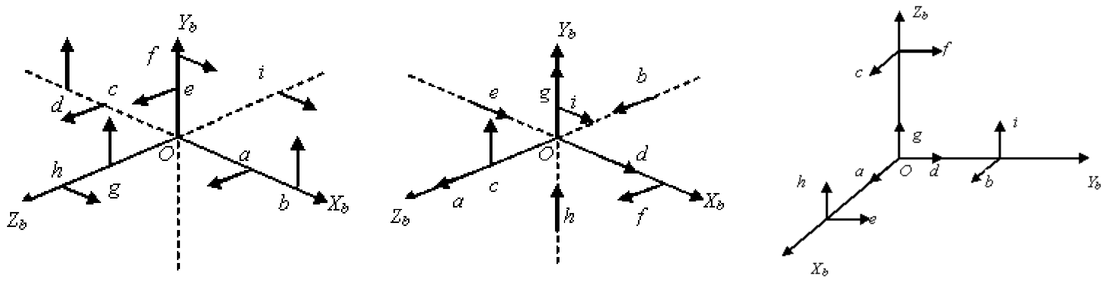


Figure 1. Configuration of Six Accelerometer

Figure 1 proposed four installation ways, the principles of (a) and (b) were same, which was suitable for slender cylinder carrier. Because of the different of two lever arm effects, to the same size accelerometer error, the calculated values of angular acceleration were different. The collocation method of (c) also was suitable for slender cylinder carrier. The sensing axis of accelerometer along each face of diagonal line direction, when each edge of parallelepiped was same, this allocation scheme was suitable for carrier such as satellites etc, similar to a sphere or cube. The configuration of (d) was suitable for triangular prism shape carrier, compared with the accelerometer allocation scheme of non-gyro strap-down inertial navigation, which could adjust length of triangular prism based on characteristics of different carriers, and had the characteristic of the flexible installation. Shi Zhen, Ma Shu-tian, Yi De-jin and others proposed computation algorithm of angular velocity at the same time, specific force by the accelerometer output could get the angular acceleration of carrier, and integrate could get angular velocity. Because of the error of angular velocity is accumulated gradually with change of time, it affected the navigation accuracy greatly. But if effective filtering algorithm was used, the resolving accuracy could be improved to a certain extent. The precision of resolving allocation scheme was low, while the price was low, suitable for short time navigation applications such as short-range anti-tactical ballistic missile etc.

The installation site of accelerometer in nine-accelerometer allocation scheme was shown in Figure 2.

Figure 2 proposed three installation ways, under the influence of the accelerometer measurement error, the allocation scheme of (a) would produce higher angular velocity error, meanwhile, as the computation method similar with six-accelerometer, the angular velocity error was accumulating fast with change of time. The allocation scheme of (b) would not appear the phenomenon of unlimited accumulation of error similar with (a), its error was bounded, so it was better than the way of (a). The allocation scheme of (c) proposed by Wang Jin-song and others made full use of the redundant information of accelerometer output to complete the resolving, effectively inhibit the iterative error. Angular velocity computation algorithms of allocation scheme of (a) and (b) were different from (a). Specific force of accelerometer output could be used to achieve angular acceleration of carrier and its absolute value, then integrated the angular acceleration and got angular velocity, the sign could be look as the sign of the absolute value to achieve angular velocity of body, error of which was bounded. So it effectively inhibited the navigation error. The cost of nine-accelerometer configuration was higher than that of six-accelerometer, but nine-accelerometer improve the system accuracy of the use of redundant information.



(a) (b) (c)

Figure 2. Configuration of Nine Accelerometers

The installation site of accelerometer in ten-accelerometer allocation scheme was shown in Figure 3, which solved CCF (Course Correcting Fuze) to a certain extent. It had the characteristics of position of center of mass of body changed over time and inertial measurement unit was not installed in the carrier near the center of mass.

Figure 4 showed the allocation scheme of seven-accelerometer and single-Gyro, although the computation method of angular velocity was similar with six-accelerometer, Gyro was configured, therefore, calculation of angular velocity on one direction was more accuracy, accordingly, the problem of calculate results divergence over time was overcome, and system accuracy was improved, while the system overload-proof dropped.

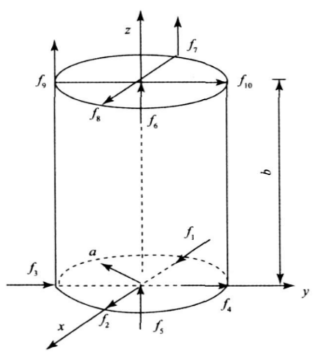


Figure 3. Configuration of Ten Accelerometers

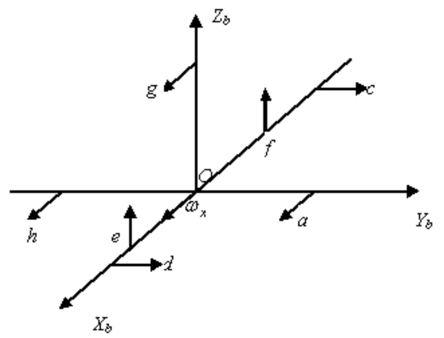


Figure 4. Configuration of Gyro and Multi Accelerometers

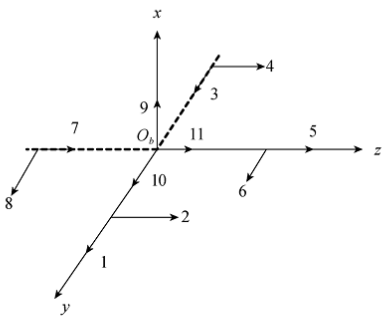


Figure 5. Configuration of Eight Accelerometers

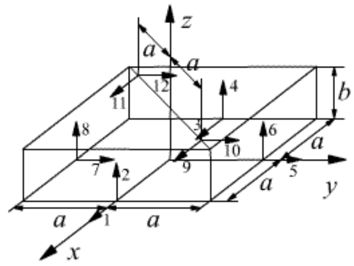


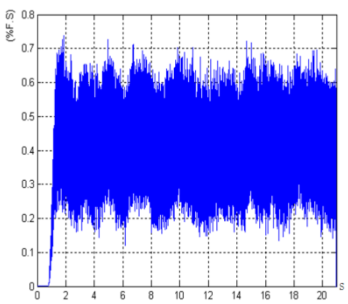
Figure 6. Configuration of Twelve Accelerometers

Literature [9] expounded design of eight-accelerometer inertial navigation system in the trajectory plane; the allocation scheme was shown in the Figure 5.

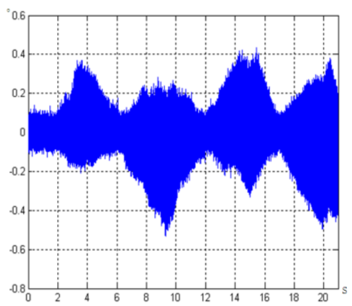
In the figure, X is bomb axis, eight accelerometers were installed in the YOZ plane, the distance between each accelerometer and axle center is a. It got angular velocity by computation, and the static and dynamic calibration. Because of the scheme using 2-D installation of accelerometer, lacking of the accelerometer on bomb axis direction, the error would increase quickly with the change of time, and affected precision of resolving greatly, which had to be revised.

Literature [10] expounded design of twelve-accelerometer inertial navigation system of high spinning projectile; the allocation scheme was shown in the Figure6.

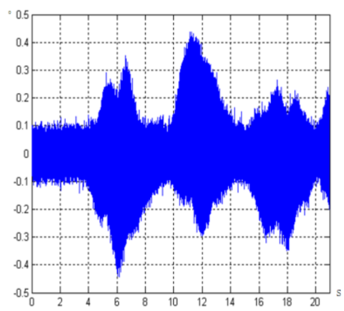
The author deduced formula of angular velocity, and took a simulation. The simulation result (Figure 7) showed that under the case of azimuth error, the error would expand rapidly, and affected precision of resolving greatly, which also had to be revised.



(a) Pitch Angle of Error Curve



(b) Roll Angle of Error Curve



(c) Yaw Angle of Error Curve

Figure 7. Each Attitude Parameter of Error Curve

3. Inertial Navigation System

Inertial navigation system (following INS for short) refers to two or more kinds of navigation equipment get together in an appropriate way, on the basis of complementary advantages in performance to get higher navigation performance than anyone inertial measurement unit. Domestic and foreign research technique for inertial navigation system includes combination of INS and Doppler navigation radar, GPS/INS System, INS/Star Sensor, INS/OD, GPS/SST/SINS, Magnetometer/MEMS Gyroscope/Accelerometer, Combination of Geomagnetism and Gyro, combination of Magnetometers and MEMS Gyro [11], MEMS Gyro/ Accelerometer/Micro Magnetometer [12], combination of Geomagnetism And Solar Direction, GPS/ Geomagnetism, Polarized-light Assisting with Geomagnetism and GPS etc.

Inertial navigation system proposed first was made up of INS and Doppler navigation radar, used long-term high precision characteristics of Doppler radar to revise short-term high precision of INS, improved precision of navigation. The technique of combination of INS and GPS was research hotspot in recent years, two of them were all navigation equipment of global, all-weather and all-time, and also afforded very complete navigation data. The combination used long-term stability and moderate precision of GPS to make up the disadvantage of error accumulated with time in INS, used short-term high precision of INS to make up the disadvantage of GPS receiver's error increased when disturbed and lost of signal when in block, gave full play to their respective strengths, learned from each other. The system had characteristics such as simple structure, high reliability, small size, light weight, low cost etc. For the reason of GPS requires external measuring devices, it was limited on the application. CCD optical sensor could also obtain the information of air target attitude, made a data fusion with INS, could also revise the position, velocity and attitude angle of INS, and improved the accuracy of attitude determination to some extent. In the year of 2006, the combination of GPS, SST and SINS proposed by Kang Guo-hua and others used modified aggregated filtering to make a data fusion with multi-sensor information and used the most estimation method of navigation mode, ballistic missile for the application object, simulation result showed that the combination could improve navigation precision of missile, filtering algorithm was stable and reliable, whether it was feasible for the live ammunition needed to be verified.

Introducing of magnetometer in INS could make up the disadvantage of Gyro's zero-drift error accumulation. The combination attitude determination of three axial magnetometer and tri-axial rata Gyro proposed by Bao Ya-qi and others also solved the problem of blind zone of exploration exist in magnetometer, in addition, Xue Liang and others also proposed attitude determination system based on MEMS Gyro, accelerometer and micro magnetometer, which had advantages of small volume, low cost and reliable performance etc. The two schemes successfully verified only through the single-axis turntable, accuracy and stability of more comprehensive and detailed verification system needed with the high-precision three-axis non-magnetic turntable to complete.

Geomagnetic sensor as a sensitive device to measure the geomagnetic signal, had been widely used in the flight attitude measurements, Cao Hong-song and others proposed attitude detect technique by combination of geomagnetism and Gyro, which strap down installed the 3-D geomagnetic sensor and solid-state MEMS Gyro on the missile body, sensitive axis of the geomagnetic sensor were at the three axial direction of the body coordinates, sensitive axis of Gyro correspond to vertical axis of projectile body, and used single axis Gyro to measure projectile body's one attitude angular velocity, and reused three-axis geomagnetic sensor to detect projection on the body coordinates of the geomagnetic vector, and simultaneously solved 3-D attitude of missile body by using single-point algorithm. The technique was easy to meet real-time requirements and error was not cumulative, solid-state characteristics of the program was suitable for the use of conventional ammunition, while silicon micro-gyroscope had initial temperature-drift characteristics, which must be compensated when in service, in addition, blind zone existed in geomagnetic detection, in application it could ensure continuous, reliable of measurement data by the method of adding redundant sensors. In the year of 2001, Huang Zheng and others proposed geomagnetism and solar direction attitude measurement system, it consisted of three axis geomagnetic position sensor solid united on the barycenter of projectile and solar attitude angle sensor solid united on the missile, system error was not cumulative, precision of measurement was higher, impact resistance was better, but when solving pitch angle, yaw angle and roll angle by using solar attitude angle, the selection of the ground coordinates was certain constraints. When bringing together geomagnetism and GPS technology to achieve projectile position and attitude angle measurement, problems related to be correction of trajectory correction was solved, but because of the ultimate goal for the attitude angle of trajectory correction measurement was the full-attitude real-time detection, geomagnetic detection attitude determination technology is not very accurate, therefore, it should be combined with other attitude determination technology to achieve fusion of a variety of attitude angle detection technology, so as to more precise guidance. On the basis and combined with the technology of polarization-sensitive neural structures from the sand ant's compound eye, in the year of 2009, Fan Zhi-guo and others designed a kind of air polarization information detection and navigation sensor, which achieved the organic integration of polarized-light, geomagnetism and GPS by self-designed test platform.

4. Conclusion

People during the course of study on flight attitude testing technology, simple use of the inertial navigation system, inevitably bring about the error accumulation over time. Although the INS measurement technology with GPS, the geomagnetic sensor and other measurement unit to a certain extent, eliminate the error accumulation, it also brings the problems such as difficult computation algorithm, low precision of computation result, the measurement unit inherent adverse characteristics etc. In the future process of study and development, if the following problems can be solved, the impacts to the practical application of flight attitude test technology in the military may be far-reaching.

Accurate measurement of the measurement unit installation error: installation error in the system is inevitable, small error or "zero" error is the pursuit of the goal of researchers, non error is unrealistic, the problem of measuring error accurately and thus eliminating the error waits to solved.

The precision of the test system: some designs of INS are feasible in theory, but the result is not satisfactory in practical applications, may be for the reason of the manufacture technology of system. Believe that with the development of high-tech electronic technology, the problems such as the cost, difficulty and precision of circuit production will be solved in the near future.

Measurement unit inherent characteristics: In the INS, when the measurement units such as GPS and magnetometer sensor are used, although the error accumulation of INS is suppressed, at the same time inherent new error is brought in, method to eliminate all kinds of errors contained in the system needs to be further solved.

The design of verification platform: before any kind of flight attitude test system is used practically, it shall be strictly verified on the correctness, accuracy, reliability, a test platform that simulate the actual flight state of air target should be set up as soon as possible, at the same time, how to ensure and eliminate the precision and error of test platform is also a task need to be solved.

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