Application and analysis of an electronic–mechanical dual stable platform for radars with a three-axis stable turntable

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Abstract: This study proposes the concept of an electronic–mechanical dual stable platform for radars with a three-axis stable turntable. Based on an assumption, an electron stable equation of the first order is applied to the beam pointing correction of the radar with three-axis stable turntable based on the equivalence principle. Furthermore, through a comparative analysis of two kinds of algorithms, it is shown that when the instantaneous value of the tracking error in the platform servo-loop of the mechanical platform is smaller than a certain range, assuming the conditions are established, the error method of the electron stable equation of the first order can directly replace the electron stable equation of the second order that is applied to the spatial orientation correction of the radar beam to improve computational efficiency. At the same time, error analysis was performed on the data link of the dual stable platform.

1 Introduction

A ship-borne radar with a three-axis stable turntable is generally installed in the main mast area of the ship. Owing to the limitation of mass and volume, and influenced by the wind load, the tracking error in the platform servo-loop [1] of the mechanical platform is large and the lag is serious, which is not conducive to the improvement of the overall accuracy of the radar. To improve the precision, on the basis of the mechanical platform to overcome the ship's wobble, consider introducing the electron stable equation of the first order to further modify the spatial direction of the radar beam. At the same time, in the actual-use environment, the vibration of the ship's main mast area will seriously interfere with the normal operation of the level-measurement equipment. Ways of obtaining the pitch angle and roll angle of the datum of the stable turntable with respect to the geoids cannot be ignored.

2 Electronic–mechanical dual stable platform

An electronic–mechanical dual stable platform is divided into a mechanical stable platform [2] and an electron stable platform. The mechanical stable platform refers to a stable platform composed of a pitch gimbal and a roll gimbal [3]. The electron stable platform refers to the error method using an electron stable equation of the first order.

The dual stable platform first uses a mechanical platform to overcome the pitch angle and the roll angle of the ship to complete the first stabilisation. After overcoming most of the swing angles of the ship, the tracking error in the platform servo-loop of the mechanical platform is used as the data source [4] of the electron stable equation of the first order for the first time to calculate the deviation of the current radar beam pointing to the azimuth angle and elevation angle. The correction is then performed to eliminate the influence of the tracking error in the platform servo-loop on the spatial orientation of the radar beam.

According to the structural characteristics of the three-axis stable turntable, it is assumed that the planes of motion of the pitch angle and the roll angle of the mechanical platform coincide with the planes of motion of the pitch angle and the roll angle of the ship. At this time, the pitch angle of the mechanical platform and the pitch angle of the ship can be arithmetically operated. The roll angle of the mechanical platform and the roll angle of the ship can also be arithmetically operated. The tracking error in the platform servo-loop of the mechanical platform is equal to the pitch deviation and the roll deviation of the datum of the stable turntable in the pitch direction and the roll direction with respect to the geoids at the current time. According to the unified national ship specification, when the sign of the attitude angle of the ship and the sign of the attitude angle of the mechanical platform meet the specifications, according to the equivalent figure, the sign of the tracking error in the platform servo-loop will also conform to the unified specification. The tracking error in the platform servo-loop can be directly brought into the electronic platform as a signed value. The first stability of the mechanical platform overcomes most of the swing angle of the ship, providing a good basis for the correction of the electronic platform. The secondary stability of the electronic platform improves the control accuracy of the entire system.

3 Error analysis of data transmission link and comparison of different algorithms

3.1 Error analysis of data transmission link in the dual stable platform

It is an electrical connection between a stabilised gyrocompass and a resolver-to-digital converter for a given signal. Stabilised gyrocompass gives the attitude angle of the ship's swing [3], and the angle is encoded by the converter. The code value acts as the given signal of the platform servo-loop of the mechanical platform. The synchroniser for feedback is connected to the platform gimbals by the coupling, and the gimbal angle is transferred to the resolver-to-digital converter for a feedback signal, and the angle is encoded. The code value acts as the feedback signal of the platform servo-loop of the mechanical platform.

It is an electrical connection between the synchroniser for feedback and the resolver-to-digital converter for a feedback signal. The tracking error in the platform servo-loop is the difference between the given signal and the feedback signal. The tracking error in the platform servo-loop is sent to the electronic platform. It is a mechanical connection between the datum of the mechanical platform and the platform gimbals, which is outside the platform servo-loop of the mechanical platform.

From an analysis of the structure of the data link of the electronic–mechanical dual stable platform, the link error is divided into two parts: link error of the mechanical platform and link error of the electronic platform (Fig. 1).

Link error of the mechanical platform: Link error of the mechanical platform includes the mechanical transmission error...
and the angle error [1] of the platform. The mechanical transmission error is mainly caused by the manufacturing error and the installation error, which is a repeatable random error [5]. The installation error includes the installation error of the synchroniser for feedback and the installation error of the datum of the mechanical platform. It is a mechanical connection between the datum of the mechanical platform and the platform gimbal, which is outside the platform servo-loop of the mechanical platform.

The mechanical transmission error is directly detected by static detection. Specifically, the platform is first locked in a horizontal position. Divide the turntable into 24 equal parts per week. A digital level measuring instrument is placed at the base of the mechanical platform. Use a computer to control the motor, with very low speed to turn the turntable. When arriving at each equal point, the motor stops rotating, read the display value of the measuring instrument in the pitch motion and roll motion, respectively. The display is the mechanical transmission error between the platform datum and the platform gimbals.

The measurement block diagram is shown in Fig. 2.

The curve of the mechanical transmission error is shown in Fig. 3.

Through static experiments, both limit values of the mechanical transmission error in the pitch motion and roll motion at 7′, and the root-mean-square value \( \sigma_{\text{mech}} \) is 5.12′ in the pitch motion and 4.45′ in the roll motion.

\[
\sigma_{\text{tot}} = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2} = 1.46′.
\]

\[
\sigma_{\text{tot}} = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2} = 0.00634° = 0.38°.
\]

\[
\sigma_{\text{tot}} = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2} = 1.46′.
\]

The angle error of the given signal is the digitiser error. It is included in the measurement error of synchronicity for feedback and the error of the encoder conversion and the quantisation error. The synchronicity for feedback adopts a zero-level precision synchronous machine. According to the requirement of the zero-level precision index, the max angle error of the synchronous machine is no more than ±3°. Calculate the relative divergence coefficient by 1/3, the root-mean-square value \( \sigma_3 \) is no more than ±0.33′. The tracking rate of the converter is much larger than the rate of the ship's sway, so the dynamic lag is very small. This value will not be considered. The number of shaft encoders is 16 bits. The unit of minimum quantisation error \( q_1 = 360°/(2^{16}) = 0.005493° = 0.32959′. \) It is larger than the resolution of the encoder 0.3′, so the root-mean-square value of the quantisation error \( \sigma_2 = q_1/(12)^{1/2} = 0.00159° = 0.095′. \) The root-mean-square value of the angle error of the given signal \( \sigma_0 = (\sigma_1 + \sigma_2)^{1/2} = 0.34′. \)

The angle error of the feedback signal is also the digitiser error. It includes the measurement error of synchronicity for feedback and the error of the encoder conversion and the quantisation error. The synchronicity for feedback adopts a zero-level precision synchronous machine. According to the requirement of the zero-level precision index, the max angle error of the synchronous machine is no more than ±3°. Calculate the relative divergence coefficient by 1/3, the root-mean-square value \( \sigma_3 \) is no more than ±1′. The max angular speed of the synchronous machine is far greater than the max speed of the antenna, so the dynamic hysteresis error is very small. This value will not be considered. A 14-bit resolver-to-digital converter is used as the angle encoder of the feedback signal. The resolution is 0.3′. The limit deviation is not >±3′. Calculate the relative divergence coefficient by 1/3, the root-mean-square value \( \sigma_3 \) is no more than ±1′. The tracking rate of the converter is much larger than the rate of the antenna, so the dynamic lag is very small. This value will not be considered. The number of shaft encoders is 14 bits. The unit of minimum quantisation error \( q_2 = 360°/(2^{14}) = 0.021973° = 1.31838′. \) It is larger than the resolution of the encoder 1.3′, so the root-mean-square value of the quantisation error \( \sigma_2 = q_2/(12)^{1/2} = 0.00634° = 0.38°. \) The root-mean-square value of the angle error of the feedback signal \( \sigma_0 = (\sigma_1 + \sigma_2)^{1/2} = 1.46′. \) Since the platform servo-loop is adopted for the platform rolling frame tracking, the root-mean-square value of the angle error of the feedback signal is less than the calculated value in practice.

**Link error of the electronic platform**: The electronic platform receives the tracking error in the platform servo-loop of the mechanical platform in real-time and reads the course signal and relative bearing signal of the current time. Intercept precision of the data bits in the calculation of the electronic platform and read the real-time performance of the course signal and relative bearing signal and the tracking error in the platform servo-loop, and the
correctness of the data transmission process can be determined by using a high-performance computer and specific data transmission guaranteed, so the link error of the electronic platform mainly is the error of input data, including the tracking error in the platform servo-loop of the mechanical platform, the angle error of the course signal and the angle error of the relative bearing signal.

The tracking error in the platform servo-loop is the difference between the given signal and the feedback signal, so the accuracy of the tracking error in the platform servo-loop depends on the angle error of the given signal and the angle error of the feedback signal. The angle error of the given signal $\sigma_{in} = 0.34'$ and the angle error of the feedback signal is $\sigma_{fb} = 1.46'$. As a result, the data transmission of the pitch angle and the roll angle is exactly the same, at the same time the angle error of the given signal and the angle error of the feedback signal are not related, so the tracking error of the pitch angle and the tracking error of the roll angle are the same. The root-mean-square value of the tracking error is $\sigma_{coul} = (\sigma_{in}^2 + \sigma_{fb}^2)^{1/2} = 0.34'$.

The course signal is a 16-bit resolver-to-digital converter sent by stabilised gyrocompass, and data transmission is the same as the transmission of the given signal. Therefore, the angle error of the course signal $\sigma_{cou} = 0.34'$. In the static test, the limit value of the angle error of the relative bearing signal is equal to $7'$ and the root-mean-square value $\sigma_{static}$ is equal to 2.667'. The measured value is derived from the structural design measurement.

Since the above errors are not related, the root-mean-square value of the total error of the electronic platform is $\sigma_{electronic} = (2 x \sigma_{coul}^2 + \sigma_{static}^2)^{1/2} = 3.42'$. The total error estimation of the dual stable platform: It includes the angle error of the input signal, the angle error of the mechanical platform gimbals, and the mechanical transmission error. These errors are listed below.

The angle error of the given signal of pitch angle: $\sigma_{in} = 0.34'$. The angle error of the given signal of roll angle: $\sigma_{fb} = 0.34'$. The angle error of the course signal: $\sigma_{cou} = 0.34'$. The angle error of the feedback signal of pitch angle: $\sigma_{fb} = 1.46'$. The angle error of the feedback signal of the roll angle: $\sigma_{fb} = 1.46'$. The angle error of the relative bearing signal: $\sigma_{static} = 2.667'$. The mechanical transmission error of the pitch motion: $\sigma_{mech1} = 5.12'$. The mechanical transmission error of the roll motion: $\sigma_{mech2} = 4.45'$. Since none of the above errors are relevant, the root-mean-square value of the total error of the dual stability platform is $\sigma_{dual} = (2 x \sigma_{in}^2 + \sigma_{cou}^2 + \sigma_{static}^2 + \sigma_{mech1}^2 + \sigma_{mech2}^2)^{1/2} = 7.60'$.

### 3.2 Comparison of different algorithms

The mechanical platform of the electronic–mechanical dual stable platform adopts a type 2 system. At the same time, the tracking error in the platform servo-loop is directly used as the data source of the electronic platform. Therefore, the tracking error in the platform servo-loop that has mainly affected the direction of the radar beam has been eliminated. The factors that affect accuracy have been changed to how much error the tracking error in the platform servo-loop will directly cause as the data source of the electronic platform; in what scope, the error can be accepted and can the algorithm be applied directly to improve computational efficiency.

The error method: The tracking error in the platform servo-loop is directly used as the data source of the electronic platform. The tracking error $(P-P')$ of the pitch angle and the tracking error $(R-R')$ of the roll angle are used as the pitch angle and the roll angle of electron stable equation of the first order, respectively [7]. Analyse the transformation equations of the polar coordinates from the geoids to the radar stable turntable:

\[
X_{P} = \cos E \times [\sin(R - R') \times \sin(P - P')] \\
\times \cos(A - H) + \cos(R - R') \\
\times \sin(A - H)] - \sin E \times \sin(R - R') \times \cos(P - P')
\]

\[
Y_{P} = \cos E \times \cos(P - P') \times \cos(A - H) + \sin E \times \sin(P - P')
\]

\[
Z_{P} = \cos E \times [\sin(R - R') \times \sin(A - H)] \\
- \cos(R - R') \times \sin(P - P') \times \cos(A - H) \\
+ \sin E \times \cos(R - R') \times \cos(P - P')
\]

to obtain

\[
A_{P} = \tan^{-1}(X_{P}/Y_{P})
\]

\[
E_{P} = \sin^{-1}(Z_{P})
\]

Analyse the transformation equations of polar coordinates from the radar stable turntable to the geoids:

\[
X_{i} = \sin E_{c} \times \sin(R - R') + \cos E_{c} \times \cos(R - R') \times \sin A_{c}
\]
Y_1 = \cos E_2 \times [\cos(P - P') \times \cos A_4 + \sin(P - P') \\
\times \sin(R - R') \times \sin A_1] - \sin E_2 \\
\times \sin(P - P') \times \cos(R - R') 
(7)

\begin{align*}
A_1 &= \tan^{-1}(X/Y_1) + H \\
E_1 &= \sin^{-1}(Z_1)
\end{align*}

(see (8)) to obtain

\begin{align*}
A_1 &= \tan^{-1}(X/Y_1) + H \\
E_1 &= \sin^{-1}(Z_1)
\end{align*}

Electron stable equation of the second order: The deck of the ship is considered to be the geoids, whereas the mechanical stable turntable is considered to be the deck of the ship, and the derivation of the electronic stable equation is repeated twice. This transformation equation of polar coordinates is derived from the geoids to the radar stable turntable [7].

Analyse the transformation equation of the polar coordinates from the geoids to the radar stable turntable

\begin{align*}
X_p &= \cos E \times \sin[P \times \sin(R - R') \times \cos(A - H) \\
&+ \cos(R - R') \times \sin(A - H)] \\
&- \sin E \times \cos P \times \sin(R - R') \\
Y_p &= \cos E \times \sin[P \times \cos(P - P') \times \sin(A - H) \\
&- \sin P \times \cos(R - R') \times \cos(A - H)] \\
&+ \sin E \times \sin P \times \sin P' \times \cos P \times \cos(R - R') \\
Z_p &= \cos E \times \sin[P \times \cos P \times \cos(A - H) - \cos P' \\
&\times \sin P \times \cos(R - R') \times \cos(A - H)] \\
&+ \cos P' \times \sin(R - R') \times \sin(A - H)] \\
&+ \sin E \times \sin P' \times \sin P + \cos P' \times \cos P \times \cos(R - R')
\end{align*}

(11)

(12)

(13)

to obtain

\begin{align*}
A_p &= \tan^{-1}(X_p/Y_p) \\
E_p &= \sin^{-1}(Z_p)
\end{align*}

(14)

(15)

Analyse the transformation equation of polar coordinates from the radar stable turntable to the geoids

\begin{align*}
X &= \cos E \times \cos A_4 \times [-\sin P' \times \sin(R - R') \\
&+ \cos E_2 \times \cos(R - R') \times \sin A_1] \\
&+ \sin E_2 \times [\cos P' \times \sin(R - R')]
\end{align*}

(16)

(see (17) and (18)) (see (18)) to obtain

\begin{align*}
A &= \tan^{-1}(X/Y) + H \\
E &= \sin^{-1}(Z)
\end{align*}

(19)

(20)

\begin{align*}
Z_1 &= \cos E_2 \times [\sin(P - P') \times \cos(A_1 - \cos(P - P') \times \sin(R - R') \times \sin A_1] \\
&+ \sin E_2 \times \cos(P - P') \times \cos(R - R')
\end{align*}

(8)

\begin{align*}
Y &= \cos E_2 \times [\cos P \times \cos P' + \sin P \times \cos P' \times \cos(R - R') \\
&+ \sin(E_2 \times \sin A_1 \times [\sin P \times \sin(R - R')] \\
&+ \sin E_2 \times [\cos P \times \sin P - \sin P \times \cos P \times \cos(R - R')]
\end{align*}

(17)

\begin{align*}
Z &= \cos E_2 \times [\cos P \times \cos P' - \cos P \times \sin P' \times \cos(R - R') \\
&- \cos E_2 \times \sin A_1 \times [\cos P \times \sin(R - R')] \\
&+ \sin E_2 \times [\sin P \times \sin P' + \cos P \times \cos P \times \cos(R - R')]
\end{align*}

(18)

Comparison of two kinds of algorithms: Compare the error method with the electron stable equation of the second order, and analyse the comparison between \(A_p\) and \(A_{p1}\), \(E_p\) and \(E_{p1}\), \(A\) and \(A_1\) and \(E\) and \(E_1\) [2] to obtain:

\begin{align*}
[\sin(\Delta E_p)] &= [\sin(E_{p1}) - \sin(E_p)] < \sin(R) \times (1 - \cos P') \\
[\tan(\Delta A_p)] &= [\tan(A_{p1}) - \tan(A_p)] < \sin(P) \times \sin(R - R') \\
[\sin(\Delta E)] &= [\sin(E_{p1}) - \sin(E_p)] < \sin(R) \times (1 - \cos P') \\
[\tan(\Delta A)] &= [\tan(A_{p1}) - \tan(A_p)] < \sin(P) \times \sin(R - R')
\end{align*}

(21)

(22)

(23)

(24)

Analyse formulas (21)–(24), to derive

\begin{align*}
[\sin(\Delta E)] &= [\sin(\Delta E_p)] = [\sin(E_{p1}) - \sin(E_p)] < \sin(R) \times (1 - \cos P') \\
[\tan(\Delta A)] &= [\tan(\Delta A_p)] = [\tan(A_{p1}) - \tan(A_p)] < \sin(P) \times \sin(R - R')
\end{align*}

(25)

(26)

The differences between \(A_p\) and \(A_{p1}\), \(E_p\) and \(E_{p1}\), \(A\) and \(A_1\) and \(E\) and \(E_1\) are estimated by formulas (25) and (26). When the mechanical stable turntable overcomes the ship’s sway, the max of the instantaneous value of the tracking error in the platform servo-loop is ±2°. To estimate the instantaneous maximum value of the tracking error (\(R - R'\)) of the roll angle is 2°, the maximum value of the pitch angle (\(P\)) is 5°, the maximum value of the roll angle (\(R\)) is 20° and the maximum value of the pitch angle (\(P\)) of the mechanical stability turntable is 5°.

\begin{align*}
[\sin(\Delta E)] &= [\sin(\Delta E_p)] = [\sin(E_{p1}) - \sin(E_p)] < \sin(R) \times (1 - \cos P') \\
&= \sin(20°)(1 - \cos 5°) = 0.00137 \\
[\tan(\Delta A)] &= [\tan(\Delta A_p)] < \sin(P) \times \sin(R - R') \\
&= \sin(5°) \sin(2°) = 0.00304
\end{align*}

(27)

(28)

to obtain

\[\Delta E < \tan^{-1}(0.00137) = 0.078°\]

\[\Delta A < \tan^{-1}(0.00304) = 0.174°\]

It can be seen from the calculation results that the error method can be used when the instantaneous value of the tracking error in the platform servo-loop is <2° for the ship-borne radar with three-axis stable turntable. The difference between the elevation error introduced and the azimuth error introduced by the algorithm is not significant and is within the acceptable range. In this case, the error method can be used directly to improve calculation efficiency. At the same time, it also proves indirectly that the assumption of the electronic platform is established within a certain range.
4 Conclusion

Error analysis of the data transmission link and a comparison of two kinds of algorithms show that without considering the installation error of the antenna pedestal and the installation error of the mechanical stability platform, the control accuracy of the electronic–mechanical dual stable platform mainly depends on the control precision of the electronic platform.

Compared to a single mechanical platform, the electronic–mechanical dual stable platform can greatly improve the control precision of the radar beam direction because the tracking error in the platform servo-loop of the mechanical platform in the traditional radar has been eliminated.

According to the characteristics of the electronic–mechanical dual stable platform, the control gain of the platform servo-loop can be reduced properly to avoid the vibration of the mechanical structure.

The use of the electronic platform using the error method is a precondition; it is based on the mechanical platform and cannot be used alone.

5 References

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