Failure Detection of Tuned Dry Gyro Redundant System†

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This paper describes the configuration of a redundant attitude reference system using three Tuned Dry Gyros (TDG's), and presents the failure detection analysis required for fail-safe operation of the system, and the quantitative evaluation of detection delay.

Key Words: tuned dry gyro, redundant sensor system, inertial navigation

1. Introduction

The TDG is a two-degree-of-freedom (TDF) directional gyro¹⁾ from the viewpoint of dynamics, but it is usually used as a TDF rate sensor by installing the rebalance control circuit (RCC)^{2),3)}. Failure of the TDG has been defined as simultaneous degradation of its two outputs. However, referring to the failure of the RCC only, even if one of the two RCC loops is degraded, the output of the other undegraded loop is usable. In that case, the TDG plays the role of a single-degree-of-freedom rate sensor. A Strap-down Inertial Navigation Redundant Sensor System can be made up by using three TDG's, but sensor failure has to be detected without exception and as soon as possible in the system. In this paper, algorithms necessary for the failure detection are analyzed, and it is shown through numerical simulation how much time is required to detect a failure after its occurrence.

2. Orientation of TDG's in the System

Three TDG's (A, B, C) contained in the redundant system are oriented such that their output axes are arrayed on the plane yz , xz , xy (Fig. 1)⁴⁾. The outputs of TDG-A, B, C are represented by $\omega_1, \omega_2, \omega_3, \omega_4, \omega_5, \omega_6$. Equations governing the relationship between measured data (TDG outputs) and navigation reference data $\omega_x, \omega_y, \omega_z$, which are components of the vehicle angular velocity along the navigation reference axes x, y, z , are derived from Fig. 1.

$$\left. \begin{aligned} \omega_1 &= k(\omega_y - \omega_z), \quad \omega_2 = k(\omega_y + \omega_z) \quad \text{for TDG-A} \\ \omega_3 &= k(\omega_z - \omega_x), \quad \omega_4 = k(\omega_z + \omega_x) \quad \text{for TDG-B} \\ \omega_5 &= k(\omega_x - \omega_y), \quad \omega_6 = k(\omega_x + \omega_y) \quad \text{for TDG-C} \\ k &= \cos 45^\circ \end{aligned} \right\} \quad (1)$$

$\omega_x, \omega_y, \omega_z$ are obtained from these six independent equations as 21 sets of solutions.

$$\omega_x = \omega_{ix}, \quad \omega_y = \omega_{iy}, \quad \omega_z = \omega_{iz}, \quad i=1 \sim 7 \quad (2)$$

Solutions for $\omega_{ix}, \omega_{iy}, \omega_{iz}$ are presented in Table 1. Solutions in No. 1 and 2 consist of two outputs

Fig. 1 Orientation of three TDG's

Table 1 Solutions for $\omega_x, \omega_y, \omega_z$

No.	ω_x	ω_y	ω_z
1	$\omega_{1x} = k(\omega_4 - \omega_3)$	$\omega_{1y} = k(\omega_1 + \omega_2)$	$\omega_{1z} = k(\omega_2 - \omega_1)$
2	$\omega_{2x} = k(\omega_5 + \omega_6)$	$\omega_{2y} = k(\omega_6 - \omega_5)$	$\omega_{2z} = k(\omega_3 + \omega_4)$
3	$\omega_{3x} = -k(2\omega_3 + \omega_1 - \omega_2)$	$\omega_{3y} = k(2\omega_1 + \omega_3 + \omega_4)$	$\omega_{3z} = -k(2\omega_1 + \omega_3 - \omega_6)$
4	$\omega_{4x} = k(2\omega_4 + \omega_1 - \omega_2)$	$\omega_{4y} = k(2\omega_2 - \omega_3 - \omega_4)$	$\omega_{4z} = k(2\omega_2 + \omega_3 - \omega_6)$
5	$\omega_{5x} = k(2\omega_5 + \omega_1 + \omega_2)$	$\omega_{5y} = -k(2\omega_5 + \omega_3 - \omega_4)$	$\omega_{5z} = k(2\omega_3 + \omega_4 + \omega_6)$
6	$\omega_{6x} = k(2\omega_6 - \omega_1 - \omega_2)$	$\omega_{6y} = k(2\omega_3 + \omega_3 - \omega_4)$	$\omega_{6z} = k(2\omega_4 - \omega_3 - \omega_6)$
7	$\omega_{7x} = -k(\omega_2 - \omega_4 - \omega_6)$	$\omega_{7y} = k(\omega_2 - \omega_4 + \omega_6)$	$\omega_{7z} = k(\omega_2 + \omega_4 - \omega_6)$

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of only one gyro, those in No. 3~6 consist of one output of each gyro and two outputs of the other gyro, and those in No. 7 consist of one output each of all three gyros.

3. Failure Detection Procedure

Failure can be detected by comparing the amount of difference between the seven equations which are extracted as the same angular velocity along each navigation reference axis x , y , z . For example, when δ_1 and δ_2 are set to be the difference between ω_{1x} and ω_{3x} and ω_{1x} and ω_{2x} respectively, if none of the outputs of the TDG's have failed, then

$$\delta_1 = \delta_2 = 0 \quad (3)$$

is obtained, but if output ω_1 has failed, δ_1 , which contains ω_1 , differs from δ_2 , which does not contain ω_1 , and the following relation is obtained.

$$|\delta_1| > |\delta_2| = 0 \quad (4)$$

However, the output of a TDG is usually measured with errors⁵⁾ proper to itself and is influenced by interaction effect³⁾, and even if a TDG can be regarded as being unfailed, the seven values of angular velocity about the same navigation reference axis don't precisely agree. For this common event in TDG's, the concept of "threshold (THR)" is introduced here. And, because errors whose mean values are nearly zero can be neglected due to their slight influence on the mission, the failure detection procedure is promoted by comparing the size of the integral of the differences of the outputs presented in Table 1 with the THR, as shown in the following.

$$\left| \int \delta_1 dt \right| > \text{THR} > \left| \int \delta_2 dt \right| \quad (5)$$

The above inequality would tend to show that ω_1 is degraded; however, there exist a great many such inequalities derived from the solutions of Table 1. In this paper, when the unequal state as shown in equation (5) occurs five times in succession, the related sensor output (for example, ω_1) is judged to be failed. These succession procedures are carried out in order to avoid false alarm (FALSA)⁶⁾ in which an unfailed sensor is judged to be failed and missed alarm (MISA)⁶⁾ in which a failed sensor is judged to be unfailed.

For a two-axis failure of any one gyro only, comparisons between the navigation data which contain two outputs of one gyro and those which contain four outputs of the other two gyros are required. For example, in the case of simultaneous failure of ω_1 and ω_2 of TDG-A, comparison inequalities are as follows.

$$\left. \begin{aligned} & \left| \int (\omega_{3y} - \omega_{5y}) dt \right| > \text{THR} > \left| \int (\omega_{1x} - \omega_{2x}) dt \right| \\ & \left| \int (\omega_{4y} - \omega_{6y}) dt \right| > \text{THR} > \left| \int (\omega_{2y} - \omega_{6y}) dt \right| \\ & \left| \int (\omega_{3z} - \omega_{6z}) dt \right| > \text{THR} > \left| \int (\omega_{5z} - \omega_{6z}) dt \right| \\ & \left| \int (\omega_{4z} - \omega_{5z}) dt \right| > \text{THR} > \left| \int (\omega_{2z} - \omega_{5z}) dt \right| \end{aligned} \right\} \quad (6)$$

If all of the above four inequalities are satisfied, then the outputs ω_1 and ω_2 are regarded to be simultaneously degraded. Left and right members of inequalities (5) and (6) are used to detect the failure of TDG-A and to make clear that the unfailed sensors (TDG-B, -C) are operating normally.

4. Simulation Results and Considerations

Here, failure is defined as the phenomenon in which the output of a TDG (ω_i , $i=1\sim6$) is remarkably different from the desired value. Through numerical simulation, the speed of failure detection when adding errors (criterion of failure) to the TDG output is evaluated quantitatively. Inputs applied to the TDG are assumed to be sinusoidal.

$$\omega_{ink} = \omega_{0k} \sin(2\pi f t + \phi), \quad k = x, y, z \quad (7)$$

ω_{0x} , ω_{0y} and ω_{0z} are amplitudes of the input, and f and ϕ are frequency and phase. ϕ is assumed to be zero in this simulation because its value doesn't influence the detection delay. ω_x , ω_y and ω_z don't precisely coincide with inputs ω_{inx} , ω_{iny} and ω_{inz} because of errors common to TDG (including failure)⁵⁾, interaction effect³⁾ and phase delay in the RCC^{2),3)}. The output error (failure) is presented in the following equation with first order time lag.

$$\delta\omega = \delta\omega_0 \{1 - \exp(-t/\tau)\}, \quad \tau = 0.05 \text{ s} \quad (8)$$

The THR is determined by simulation, taking

Fig. 2 Example of numerical simulation result in the case of ω_x -failure

the avoidance of FALSA and MISA into consideration, and here its value was prescribed according to the dimensions of the TDG⁷⁾ developed in JAPAN as:

$$\text{THR} = 0.0002 \text{ [deg]} \quad (9)$$

Performance index ΔT is defined as the delay time from occurrence to detection of the failure. An example of the numerical calculations of ΔT is shown in Fig. 2. The values of $\delta\omega_0$ are 10 and 50 (deg/h) in the upper and lower parts of the dot-dash-line of Fig. 2, respectively. It is clearly seen from Fig. 2 that ΔT decreases with an increase of error magnitude $\delta\omega_0$, but does not depend on the frequency f . And ΔT increases when ω_x , ω_y and ω_z are comparatively large because the influence of interaction³⁾ on the outputs is larger. Moreover, it has been clarified through simulation that simultaneous degradation of the two outputs of each TDG can be easily detected by using the comparison method in equation (6), also.

5. Concluding Remarks

As a preliminary study concerning the configuration of a Redundant Attitude Reference System

in which three TDG's are non-orthogonally oriented, a fundamental concept for detecting not only single-axis failure but also two-axis failure has been established in this paper. However, the following points remain for future study. (1) In order to detect the failure without waste of calculation, it will be necessary to clarify which of the many different inequalities derived, such as equations (5) and (6) from Table 1, should be selected. (2)

When smaller errors occur detection is more difficult; therefore, it will be necessary to estimate the output errors by using such as estimators as Kalman filters to prevent FALSA and MISA.

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