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MECHANISMS OF ERROR DEVELOPMENT IN INERTIAL NAVIGATION SYSTEMS

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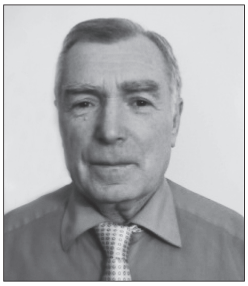

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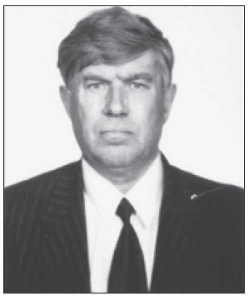

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Abstract. The processes of error development in an inertial navigation system are analysed. With this aim, the standard structures of error development were extracted in the inertial system. Error development was defined in the standard structures. Error development in the inertial navigation system is concluded according to the results obtained in the work.

Keywords: inertial navigation system, system structure, standard structural element of system, error of structural elements, channel error, system error.

1. Introduction

Inertial navigation systems are the basis of the flight navigation systems of modern aircraft. An inertial navigation system has a number of specific features. It produces large amount of information about the parameters of the aircraft, and it operates autonomously. The inertial system has a very complex flowchart, however. Errors in the inertial navigation system are increasingly accumulated over time (Moir, Seabridge 2006).

The mechanism of error accumulation in the inertial navigation system is the following. The error appears in an element of the inertial navigation system. This error of the element is input into the block diagram of the inertial navigation system. There it is repeatedly transformed in the structural elements of the system and is transformed into an error of the whole inertial navigation system (Moir, Seabridge 2006; Trifonov-Bogdanov 1984, 1986a).

2. Development of errors in one channel of the inertial navigation system

Let us analyse the development of errors in the inertial navigation system. The analysis will be carried out for the structure of a semi-analytic type of inertial navigation system. The structure of the semi-analytic type of inertial navigation system is composed of integrators and feedback. Feedback is a switching signal correction of the angular velocity of the gyro platform. A strapdown inertial system has a similar block diagram. Here the feedback is a switching signal of the angular velocity of the aircraft relative to the earth. Besides the main loops of the structure of the inertial navigation system, there are cross connections of them (Moir, Seabridge 2006).

The analysis will be carried out for the cases in which structural elements generate the typical errors (2). The structure of the inertial navigation system includes accelerometers and integrators. A typical error of these elements is the presence of a constant signal at the output. The inertial navigation systems include also gyroscopes. The mechanical gyroscopes of the inertial semi-analytic–type system have an increasing error at the output. This takes place because the centre of gravity of the gyroscope does not coincide with its geometrical centre (Trifonov-Bogdanov 1984, 1986b). There is a moment of unbalance. Because of this, the gyro will precess.

The development of errors in one channel of the inertial system was analysed. Figure 1 represents a single channel error model of the inertial system.

The error model of one channel consists of a main circuit and the integrator path. The main circuit consists of gyro platform integrators connected in series and speed integrators. These integrators are enveloped with negative feedback.

Calculations of the main circuit errors have shown that it possesses the properties of an oscillatory circuit. In the presence of failure of structural elements, oscillations appear in the main loop. In the case of failure of the gyroscope (at its drift with the angular velocity $\omega_{\downarrow} dr0$), the speed signal at the output of the main circuit is defined as

$$\Delta(p) = \frac{1}{p} \cdot g \cdot \frac{1}{p}\left[\frac{\omega_{dr0}}{p} - \frac{1}{R_z} \cdot \Delta U(P)\right],$$

$$\Delta U(P) = \frac{q \cdot \omega_{dr0}}{p\left[p^2 + \left(\sqrt{\frac{q}{R_z}}\right)^2\right]},$$

$$\Delta U(t) = R_z \cdot \omega_{dr0} \cdot \left(1 - \cos\sqrt{\frac{q}{R_z}} \cdot t\right).$$

After the integration, we obtain a signal proportional to the distance

$$\Delta S(t) = R_z \cdot \omega_{dr0} \cdot t - \sqrt{\frac{R_z^{\delta}}{q} \cdot \omega_{dr0}} \cdot \sin\sqrt{\frac{q}{R_z}} \cdot t \,.$$

With the failure of the accelerometer (constant signal at accelerometer output Δa_o), signal speed and distance on the main circuit output are defined as

$$\Delta U(P) = \frac{1}{p}\left[\frac{\Delta a_0}{p} - g \cdot \frac{1}{p} \cdot \frac{1}{R_z} \cdot \Delta U(P)\right],$$

$$\Delta U(P) = \frac{\Delta a_0}{p^z + \left(\sqrt{\frac{q}{R_z}}\right)^z},$$

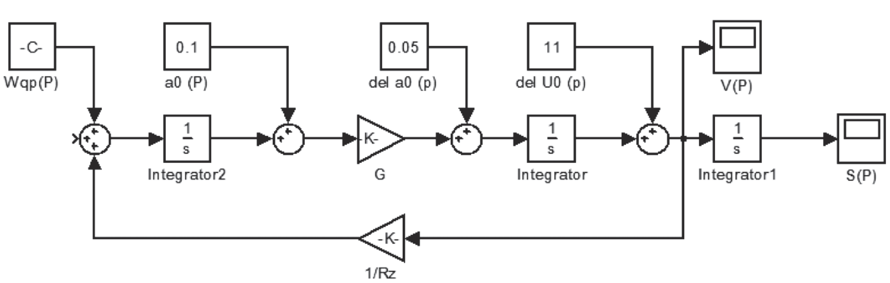

Fig. 1. Model of the error in one channel of an inertial system

$$\Delta U(t)=\sqrt{\frac{R_z}{q}}\cdot\Delta a_0\cdot\sin\sqrt{\frac{q}{R_z}}\cdot t\ ,$$

$$\Delta S(t)=\frac{Rz}{q}\cdot\Delta a_0\cdot\left(1-\cos\sqrt{\frac{q}{R_z}}\cdot t\right).$$

The structure of signal errors in speed and distance contains the components varying according to the laws of sine and cosine.

The development of channel errors was simulated for the cases when one element of the scheme operates with the error. The error of the accelerometer is 0.05 m/s^2. The error rate of the integrator is equal to 11 m/sec. The error of the platform alignment is 0.1 °. Gyro error is 0.1 °/hr. The modelling of the errors has been performed by means of the MATLAB (Simulink) program.

Figures 2 and 3 present the graphs of the time evolution of the errors of speed and distance of one channel of the inertial system for the case of gyroscope platform failure.

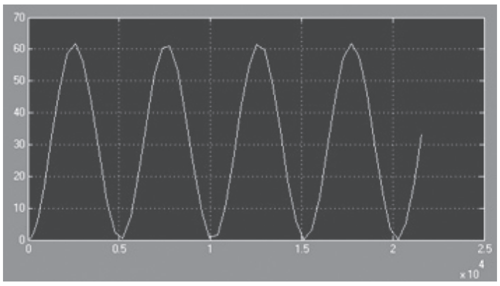

Fig. 2. The time variation in the error rate of one channel when the gyro drifts with angular velocity ω_qp0 = 0.1 grad/st

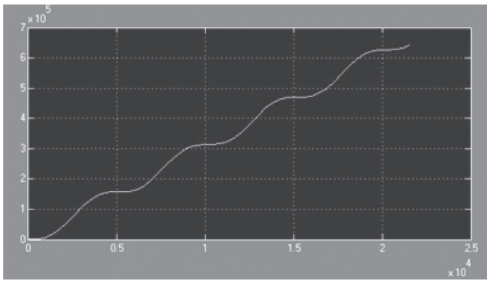

Fig. 3. The time variation of the error of the traversed path of one channel when the gyro drifts with angular velocity ω_qp0 = 0.1 grad/st

From the graphs it follows that the variable signals contain a harmonic component. Error development for a single channel for the simulation of an actual situation was modelled for the case when all the structural elements of the main circuit operate correctly. Graphs of the errors for this situation are shown in figures 7 and 8 (north channel). From the graphs it follows that the varying error signals of speed and path contain a harmonic component. This demonstrates the oscillatory nature of the main circuit of the channel of the inertial system.

The histogram in Figures 4 and 5 shows the magnitude of the errors for one channel of the inertial system for 6 hours of operation in the case of failure of one particular element.

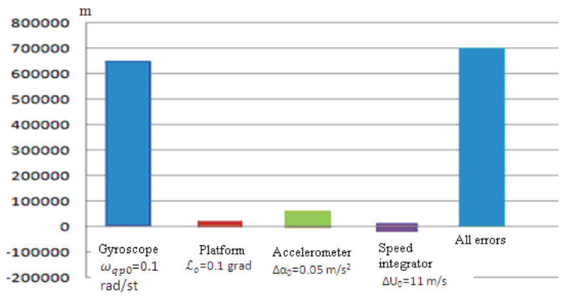

Fig. 4. The maximum error of one channel of an inertial system of distance for various cases of failures of structural elements

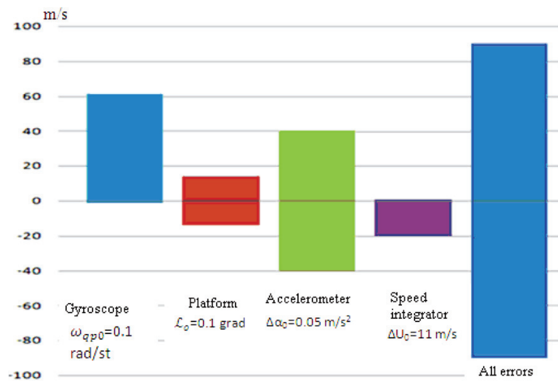

Fig. 5. The maximum error of one channel of an inertial system of distance for various cases of failures of structural elements

The location of the bar on both sides of the zero line indicates that an error has positive and negative components. Analysis of the histograms shows the following. The error of the inertial systems depends on the location of the failure of the element. The greatest error of the inertial system will take place when the element located at the beginning of the main circuit fails (the failure of the gyroscope). For a real situation when all elements operate with failures, the error of the inertial system increases.

3. Development of the errors in an inertial navigation system

The development of errors in an inertial system, when between the channels there are functional connections, was analysed. These cross connections between the channels appear due to necessity for reasons of internal adjustment.

Figure 6 represents a model of the inertial system errors when two channels are jointly operating.

In the north channel, the structural elements operate with errors. Then in the main loop of the north channel errors will be developed. These errors along the

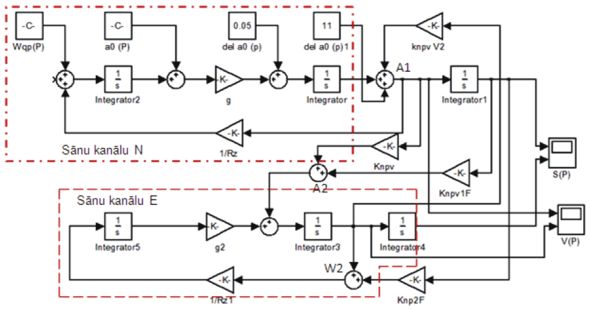

Fig. 6. Model of inertial system errors when two channels jointly operate

cross-connections will then be input to the other channel, the east channel. The east channel will also get an error. Figures 7 and 8 demonstrate the graphs of the time evolution of the errors of the two channels of an inertial system when the error goes from the north channel to the east channel of the same chain of transmission factor KprV. A signal proportional to the error of speed goes from the north channel to the east channel. It goes to a relatively non-critical point.

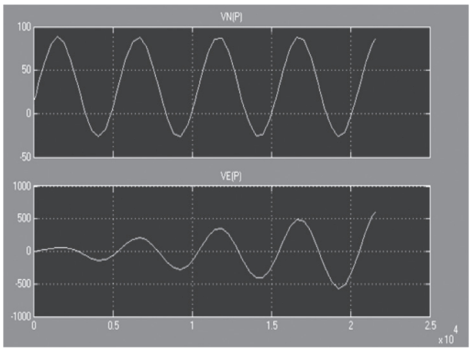

Fig. 7. Graphs of error rates of the two channels of an inertial system when between the channels there is only one cross-link with transmission factor KprV (knpv = 0.001)

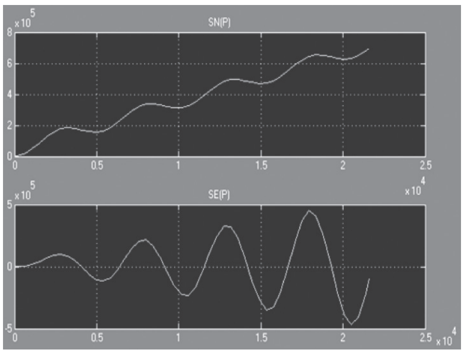

Fig. 8. Graphs of errors on both channels traversed the path of inertial systems when between the channels there is only one cross-link with transmission factor KprV (knpv = 0.001)

From the graphs it follows that the supply of an error from one (north) channel to the other (eastern) channel results in growing errors in the second (eastern) one. Errors in velocity and path in the east channel are changed in sine wave with increasing amplitude over time. Moreover, the amplitude of the error in velocity in the east channel exceeds the amplitude of the error in velocity in the north channel. The reason for this is the same tuning of the main loops of the north and east channels. The main loop of the east channel is then supplied with a resonant signal, developed in the circuit of the east channel.

With increasing number of cross-connections of the channels, errors in the east channel will grow more quickly. Inertial system errors are simulated when the north and east channels are connected with three cross-links (Fig. 6). The east channel then receives three signals from the north channel. Two signals are supplied after the integration. One of them is supplied to a critical point. Figure 9 represents the graphs of error rates of speed of two channels of an inertial system when between the channels there are three cross connections with factors of transmission knpv = 0.001, knpv1F = 0.001, and knpv2F = 0.001.

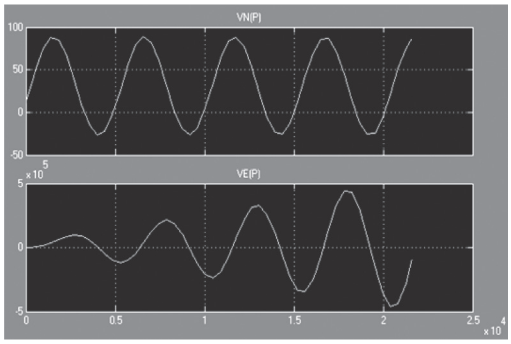

Fig. 9. The graphs of error rates of speed of two channels of an inertial system when between the channels there are three cross connections with factors of transmission knpv = 0.001, knpv1F = 0.001, and knpv2F = 0.001

From the graphs it follows that the error in velocity in the east channel is significantly increased (1000 times) in comparison with the previous case (Fig. 7).

And an even greater increasing in the errors of inertial systems will take place if its channels are connected with mutual cross-links. We determined the error of an inertial system when the east channel is supplied with three signals along three cross-connections from the north channel. There is a counter-flow of information from the east channel as well; a signal is supplied to the north channel. Such a block diagram (Fig. 6) creates a specific mechanism of error development. With the presence of the structural elements operating with errors in the north channel this channel produces an error. This error distribution along three cross-connections goes to the east channel. In the east channel an error is developed. Then this error goes to the north channel along the cross-connection. Thus a closed structure consisting of two interconnected identical main circuits has been formed. This structure has a motion of errors within closed loops. The graphs in figures 10 and 11 show the development of errors in speed and distance in the north and east channels.

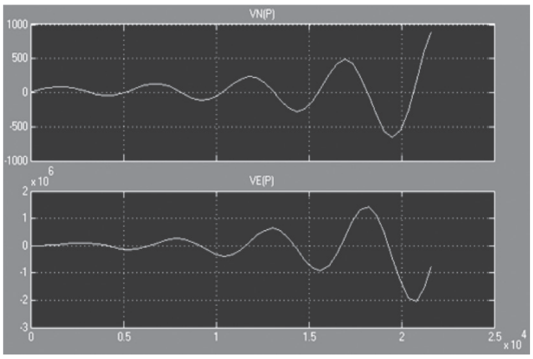

Fig. 10. Graphs of error rates of the two channels of an inertial system when between the channels there are cross-connections with coefficients of transmission knpv = 0.001, knpv1F = 0.001, knpv2F = 0.001, and knpv V2 = 0.0001

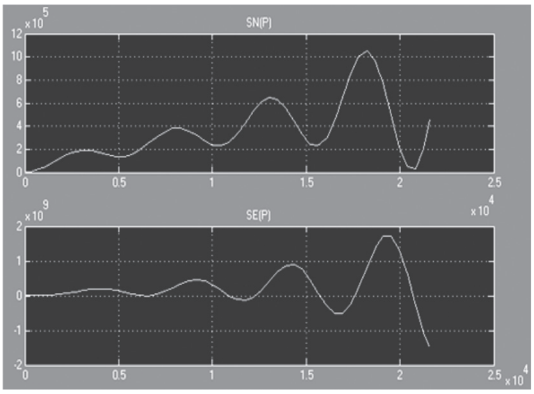

Fig. 11. Graphs of errors on both channels traversed the path of inertial systems when there is cross-connection between the channels due to transfer coefficients knpv = 0.001, knpv1F = 0.001, knpv2F = 0.001, and knpv V2 = 0.0001

From the graphs it follows that the error in speed and distance in the east and north channels grows over time. A similar situation was observed in the east channel in the previous case, when the signals from the north channel were supplied to the east channel along three cross-connections (Fig. 9). But now (Fig. 10) the errors in the east channel are higher in magnitude. In the northern channel the errors are also accumulated over time (Figs. 10, 11), although in the previous case (Fig. 9) the accuracy for speed in the north channel does not fall over time. The increase in errors over time in the north channel takes place due to the supply of a signal from the east channel along the cross-connection. The main circuit of the north channel is supplied with a signal from the analogue main circuit of the east channel. These main circuits have the same structure and configuration. Then the north channel is supplied with a resonant signal oscillating its circuit.

Thus, the analysis of the mechanisms of errors for inertial navigation systems results in a fundamental conclusion. Errors in an inertial navigation system will be always increased over time.

4. Conclusions

An inertial navigation system is a special class of aircraft measuring system. One of the characteristics of an inertial system is its structure. An inertial system is a complex structure. Each channel of an inertial system has a closed loop. The closed loop consists of two in series connected integrators covered with a negative feedback. The closed circuits of the channels of inertial systems are cross-linked with each other. Some of the cross connections include integrators.

In accordance with the structure of the inertial system, a mechanism of error development is working there. In the case of any structural element operating with error, a system error is developed in a closed circuit channel. This error is transmitted along the cross-connections into the closed loop of the second channel. In the second closed loop the error of the system also evolves. Then the error of the second closed loop is supplied back to the cross coupling between the channels in the first closed loop. In the first circuit the further development of the inertial system errors takes place, taking into account the arrival of an additional signal. As a result, the error of the inertial system will be always increased over time.

References

Moir, I.; Seabridge, A. 2006. *Civil Avionics Systems*. Wiley-Blackwell. 396 p.

Trifonov-Bogdanov, P. 1984. *Osnovy inercialnoi navigacii*. Riga: RIIGA. 79 c. (in Russian).

Trifonov-Bogdanov, P. 1986a. *Inercialnye navigacionnye sistemy vozdushnykh sudov grazhdanskoi aviacii*. Riga: RIIGA. 103 c. (in Russian).

Trifonov-Bogdanov, P. 1986b. *Osnovy inercialnoi navigacii*. Riga: RIIGA. 79 c. (in Russian).