МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ
Факультет аеронавігації, електроніки та телекомунікацій
Кафедра аерокосмічних систем управління

ДОПУСТИТИ ДО ЗАХИСТУ

Завідувач кафедри АКСУ

___________Юрій МЕЛЬНИК

“_____” ____________ 2023 р.

КВАЛІФІКАЦІЙНА РОБОТА

(ПОЯСНЮВАЛЬНА ЗАПИСКА)

ВИПУСКНИК ОСВІТНЬОГО РІВНЯ

«БАКАЛАВР»

Тема: «Комплементарний фільтр для визначення орієнтації БПЛА»

Виконавець: Євген ГАБЛЮК

Керівник: Лев РИЖКОВ

Нормоконтролер:_______________________________ Микола ДИВНИЧ

Київ 2023

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

NATIONAL AVIATION UNIVERSITY
Faculty of Air Navigation, Electronics and Telecommunications
Aerospace Control Systems Department

ACCEPT TO PROTECTION

Head of the ACS Department

____________ Yurii MELNYK

“_____” ____________ 2023 y.

QUALIFICATION PAPER

(EXPLANATORY NOTE)

FOR THE ACADEMIC DEGREE OF BACHELOR

Subject: «Complementary filter for determining the orientation of the UAV»

Performer: Yevhen HABLIUK

Supervised: Lev RYZHKOV

Standards inspector: Mykola DYVNYCH

Kyiv 2023

НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ

Факультет аеронавігації, електроніки та телекомунікацій

Кафедра аерокосмічних систем управління

Спеціальність: 151 "Автоматизація та комп'ютерно-інтегровані технології"

ЗАТВЕРДЖУЮ

Завідувач кафедри

_________ Юрій МЕЛЬНИК

“ ____ ” __________ 2023 р.

ЗАВДАННЯ
на виконання кваліфікаційної роботи

Габлюка Євгена Олександровича

1. **Тема проекту (роботи):** “Комплементарний фільтр для визначення орієнтації БПЛА”

   Затверджено наказом ректора від «13» квітня 2023 р. No 507/ст
2. **Термін виконання проекту (роботи):** з 22.05.2023 р. до 22.06.2023 р.
3. **Вихідні дані до проекту (роботи):** Показання гіроскопу та акселерометра, вимоги до допустимих значень похибки, визначення оптимальної схеми комплементарного фільтра, середовище Simulink.
4. **Зміст пояснювальної записки (перелік питань, що підлягають розробці):**
   - а. Актуальність використання комплементарного фільтра для визначення орієнтації БПЛА;
   - б. Огляд теоретичної інформації з приводу рішення задачі;
   - в. Огляд основних схем побудови комплементарних фільтрів;
   - г. Розробка способу компенсації лінійних прискорень за допомогою комплементарного фільтра

5. Перелік обов’язкового ілюстративного матеріалу: Графіки результатів моделювання та розрахунків. Матеріали презентації в Power Point.

6. Календарний план-графік

№ пор.	Завдання	Термін виконання	Відмітка про виконання
1.	Отримання завдання	08.05.2023 – 11.05.2023	
2.	Формування мети та основних завдань дослідження	12.05.2023 – 13.05.2023	
3.	Аналіз існуючих методів	14.05.2023 – 19.05.2023	
4.	Теоретичний розгляд рішення задачі	20.05.2023 – 25.05.2023	
5.	Розробка оптимальних значень та схеми комплементарного фільтра	25.05.2023 – 28.05.2023	
6.	Розробка моделі з фільтраційною ланкою та аперіодичною ланкою в середовищі Simulink	28.05.2023 – 03.06.2023	
7	Дослідження статичної та динамічної похибки комплементарного фільтра	03.06.2023 – 05.06.2023	
8.	Оформлення пояснювальної записки	05.06.2023 – 07.06.2023	
9.	Підготовка презентації та роздаткового матеріалу	08.06.2023 – 11.06.2023	

7. Дата видачі завдання: “08” травня 2023 р

Керівник дипломної роботи ____________________ Л.М. Рижков
(підпис керівника) (П.І.Б.)

Завдання прийняв до виконання ____________________ Є.О. Габлюк
(підпис випускника) (П.І.Б.)

NATIONAL AVIATION UNIVERSITY
Faculty of aeronavigation, electronics and telecommunications
Aerospace Control Systems Department
Specialty: 151 "Automation and computer-integrated technologies"

APPROVED
Head of Department
________ Yurii MELNYK
"____" __________2023

Qualification Paper Assignment for Graduate Student

Habliuk Yevhen Oleksandrovych

1. Theme of the project: " Complementary filter for determining the orientation of the UAV "

Approved by rector order from «13» April 2023 No 507/ст

2. The term of the project (work): from 22.05.2023 until 22.06.2023

3. Output data to the project (work): Gyroscope and accelerometer readings, requirements for permissible error values, determination of the optimal complementary filter scheme, Simulink environment.

4. Contents of the explanatory note (list of questions to be developed):

a. The relevance of using a complementary filter to determine the UAV's orientation;
b. Review of theoretical information on the solution of the problem;
c. Overview of the basic schemes for constructing complementary filters;
d. Development of a method for compensating linear accelerations using a complementary filter

5. The list of mandatory illustrations:

Graphs of simulation and calculation results. Presentation materials in Power Point

6. Planned schedule:

№	**Task**	**Execution term**	**Execution mark**
1.	Task receiving	08.05.2023 – 11.05.2023	
2.	Purpose formation and describing the main research tasks	12.05.2023 – 13.05.2023	
3.	Analysis of existing methods	14.05.2023 – 19.05.2023	
4.	Theoretical analysis of the task solutions	20.05.2023 – 25.05.2023	
5.	Development of the optimal values and scheme of the complementary filter	25.05.2023 – 28.05.2023	
6.	Development of a model with a saturation unit and an aperiodic unit in Simulink environment	28.05.2023 – 03.06.2023	
7.	Study of static and dynamic error of a complementary filter	03.06.2023– 05.06.2023	
8.	Making an explanatory note	05.06.2023 – 07.06.2023	
9.	Preparation of presentation and handouts	08.06.2023 – 11.06.2023	

7. Date of task receiving: “08” May 2023

Qualification paper supervisor _______________ Lev RYZHKOV
(signature)

Issued task accepted _______________ Yevhen HABLIUK
(signature)

РЕФЕРАТ

Пояснювальна записка до дипломної роботи « Комплементарний фільтр для визначення орієнтації БПЛА »: 51 с., 34 рис., 9 літературних джерела.

Об’єкт дослідження: Система датчиків для визначення орієнтації БПЛА, об’єднана у комплементарний фільтр

Мета роботи: Розробка способу компенсації лінійних прискорень за допомогою комплементарного фільтра

Для досягнення цієї мети необхідно розв’язати наступні завдання:

- Проаналізувати системи орієнтації БПЛА;
- проаналізувати основні варіанти побудови схем комплементарного фільтра;
- підібрати оптимальну схему побудови і значення датчику кутової швидкості та акселерометра;
- розробити модель комплементарного фільтра з додаванням фільтраційної та аперіодичної ланок в середовищі Simulink для зменшення впливу саме лінійних прискорень на визначення орієнтації БПЛА;
- дослідити вплив статичної та динамічної похибок комплементарного фільтра.

Предмет дослідження: Модель комплементарного фільтра побудованого за принципом компенсації, з додаванням фільтраційної та аперіодичної ланок, в середовищі Simulink

Методи дослідження: Системний аналіз, математичне моделювання, теорія автоматичного керування, оптимізація та налаштування в середовищі Simulink

КОМПЛЕМЕНТАРНИЙ ФІЛЬТР, ОРІЄНТАЦІЯ БПЛА, МОДЕЛЮВАННЯ СХЕМ, ЛІНІЙНІ ПРИСКОРЕННЯ, СТАТИЧНА ТА ДИНАМІЧНА ПОХИБКИ

ABSTRACT

Explanatory note to the thesis " Complementary filter for determining the orientation of the UAV ": 51p., 34 figures, 9 literary resources.

The object of research: A sensor system for UAV orientation, combined with a complementary filter

The purpose of the work: Development of a compensation method for linear accelerations using a complementary filter

To achieve this purpose, it must be solved the following tasks:

- Analyse the UAV orientation systems;
- analyse the main variants of the complementary filter circuit design;
- select the optimal construction scheme and values of the angular velocity sensor and accelerometer;
- to develop a model of a complementary filter with the addition of filtering and aperiodic units in the Simulink environment to reduce the impact of linear accelerations on the determination of UAV orientation;
- to study the influence of static and dynamic errors of the complementary filter.

Subject of research: A model of a complementary filter based on the principle of compensation, with the addition of filtering and aperiodic units, in the Simulink environment

Methods of research: System analysis, mathematical modelling, automatic control theory, optimisation and configuration in Simulink environment

COMPLEMENTARY FILTER, UAV ORIENTATION, SCHEMES MODELLING, LINEAR ACCELERATIONS, STATIC AND DYNAMIC ERRORS

Content

Glossary

UAV - Unmanned Aerial Vehicle

CF – Complementary Filter;
MEMS - Micro Electro Mechanical Systems;

INS - Inertial Navigation Systems;
AVS - Angular Velocity Sensor;
GPS - Global Positioning System;
ACC - Accelerometer Sensor;
TF – Transfer Function.

Introduction

The latest developments in autonomous vehicle technology have made unmanned aerial vehicles (UAVs) a highly desirable option for modern military and civilian applications. These include aerial photography, pipeline and power line inspection, disaster assessment, remote sensing and cruise missile deployment.

In order to operate unmanned aerial vehicles (UAVs), whether manually or with computer assistance, it is crucial to have knowledge of their orientation, velocity, and position. However, when cost or weight limitations is an issue, the use of high-precision inertial navigation systems becomes impractical. As a result, low-cost alternatives have gained popularity, employing inertial sensors based on microelectromechanical systems (MEMS). These MEMS-based systems offer a cost-effective solution but come with certain limitations. They are inclined to increased sensor noise, drift, and impulse accelerations, which can result in potential errors in reporting roll, pitch, and yaw angles. Despite these drawbacks, inertial navigation system remains a critical component for ensuring the safe and reliable flight of UAVs, providing essential information about their orientation in three-dimensional space.

Inertial Navigation Systems (INS) performed as the fundamental on-board navigation equipment for different vehicles [6,7]. They provide comprehensive information regarding the present orientation, motion characteristics, and position of a moving object. INS incorporates sensors that measure linear acceleration and angular velocity. These sensors aid in determining the discrepancy between the coordinate system of the instrument body and the Earth coordinate system, thereby providing orientation angles such as roll, pitch, and yaw. By integrating the readings from the accelerometer, the INS enables the calculation of the positional deviation in terms of latitude, longitude, and altitude.

The key feature of a non-platform Inertial Navigation System (INS) is the rigid attachment of the inertial sensor block to the object’s axes within the body. In this case, the geographic coordinate system is not physically modeled by a gimballed platform, but is calculated analytically, requiring higher accuracy inertial sensors than platform-based systems regardless of their type.

In certain situations, it becomes necessary to employ two distinct sources of measurement to estimate a variable. However, the characteristics of the noise in these two measurements differ. One source offers accurate information primarily in the low-frequency range, while the other excels in the high-frequency range. To solve this, a complementary filter [3] is commonly utilized to combine the two signals.

The complementary filter was developed in the 1950s for use in navigation systems. The idea was to use two different types of sensors together to measure the same motion parameters, such as angular velocity and acceleration. A complementary filter is one of the options for building measurement combining schemes. As opposed

to the Kalman filter, the scheme uses two sensors, rather than a sensor and a linear model.

Gyroscopes are specifically engineered to measure the angular velocity of rotation. However, MEMS gyroscopes suffer from a limitation known as zero drift.

This issue occurs when the gyroscope ceases rotation but continues to display a non-zero value. Another drawback of using MEMS gyroscopes is the reliance on discrete integration, which inherently introduces inaccuracies in the results. Additionally, a third problem arises from the gradual accumulation of calculation errors due to the limited precision of microcontroller variables.

Accelerometers are designed to measure acceleration forces and can be used to measure vibration and tilt. The biggest problem with MEMS accelerometers is the significant error in linear accelerations caused by acceleration, deceleration, and turning of the object.

Therefore, based on the above material, the complementary filter gives us corrected information only about pitch and roll angles. For complete information about the orientation of the flying object, we also need to know the yaw angle, which is measured using a magnetometer

CHAPTER 1 MAIN TYPES OF UAV ORIENTATION SYSTEMS

1.Main types of UAV orientation systems and their analysis

There are several different orientation determination systems (ODS) for unmanned aerial vehicles (UAVs). Some of them include:

1) **Gyroscopes:** Gyroscopes play a crucial role in unmanned aerial vehicle (UAV) orientation systems. They are used as attitude sensors to measure the angular velocity or rate of rotation of the UAV around its roll, pitch, and yaw axes. By providing information about the rate of change of orientation, gyroscopes contribute to determining and maintaining the UAV’s attitude and heading.

In UAV orientation systems, gyroscopes are typically integrated as part of an inertial measurement unit (IMU). An IMU combines gyroscopes with other sensors like accelerometers and magnetometers to provide a comprehensive measurement of the UAV’s motion and orientation.

Gyroscopes provide continuous and accurate measurements of the rotational movements of the UAV. They are especially useful in estimating the rate of change of attitude, which is crucial for stabilization, control, and navigation of the UAV. By monitoring the angular velocity, gyroscopes can detect and respond to changes in orientation, allowing for precise control and maneuverability.

One common type of gyroscope used in UAV orientation systems is the MEMS (Micro-Electro-Mechanical Systems) gyroscope. MEMS gyroscopes are small, lightweight, and consume less power, making them well-suited for UAV applications. They often utilize microelectromechanical systems technology to sense and measure the rotational motion.

The output of the gyroscope is typically processed and integrated over time to obtain the UAV’s current orientation. However, gyroscopes are prone to drift, meaning that small errors can accumulate over time and lead to inaccuracies in orientation estimation. To reduce this drawback, gyroscopes are often used in combination with other sensors, such as accelerometers or magnetometers, in sensor fusion algorithms like Kalman filters or complementary filters. These algorithms combine the measurements from multiple sensors to improve accuracy and reduce drift.

In summary, gyroscopes are important components of UAV orientation systems. They provide critical information about the UAV's angular velocity and enable precise control and navigation, making them integral to the stability, maneuverability, and overall performance of UAVs.

2) **Accelerometers:** Accelerometers are another important component of unmanned aerial vehicle (UAV) orientation systems. They are used to measure the linear acceleration experienced by the UAV along its three axes: roll, pitch, and yaw. Accelerometers provide information about the UAV's motion and gravitational forces acting upon it, which helps in determining its orientation relative to gravity.

In UAV orientation systems, accelerometers are often integrated as part of an inertial measurement unit (IMU) along with gyroscopes and sometimes magnetometers. The combination of these sensors allows for a more comprehensive estimation of the UAV's attitude, position, and motion.

Accelerometers measure the acceleration forces acting on the UAV, including both linear acceleration and the acceleration due to gravity. By analyzing these measurements, the orientation of the UAV can be determined relative to the direction of gravity, providing roll and pitch angles.

Accelerometers are particularly useful for estimating the roll and pitch angles of the UAV, as they directly measure the forces acting along these axes. By integrating the acceleration measurements over time, the UAV's velocity and position can also be derived.

One challenge with accelerometers is that they are sensitive to external forces and vibrations, which can introduce noise and errors into the measurements. To address this, sensor fusion algorithms, such as Kalman filters or complementary filters, are often used to combine accelerometer data with other sensor measurements, such as gyroscopes or magnetometers. This fusion process helps reduce noise, correct for sensor biases, and improve the accuracy of the orientation estimation.

It’s important to note that accelerometers alone cannot directly measure the UAV’s yaw angle (rotation around the vertical axis). For this purpose, magnetometers or other sensors that can detect magnetic fields are often employed in conjunction with accelerometers.

To summarize, accelerometers are critical sensors in UAV orientation systems. They provide essential information about linear acceleration, gravitational forces, and relative orientation to gravity. By integrating this data with other sensor measurements, accelerometers contribute to the accurate estimation of UAV attitude, motion, and position, enabling precise control, stabilization, and navigation of the vehicle.

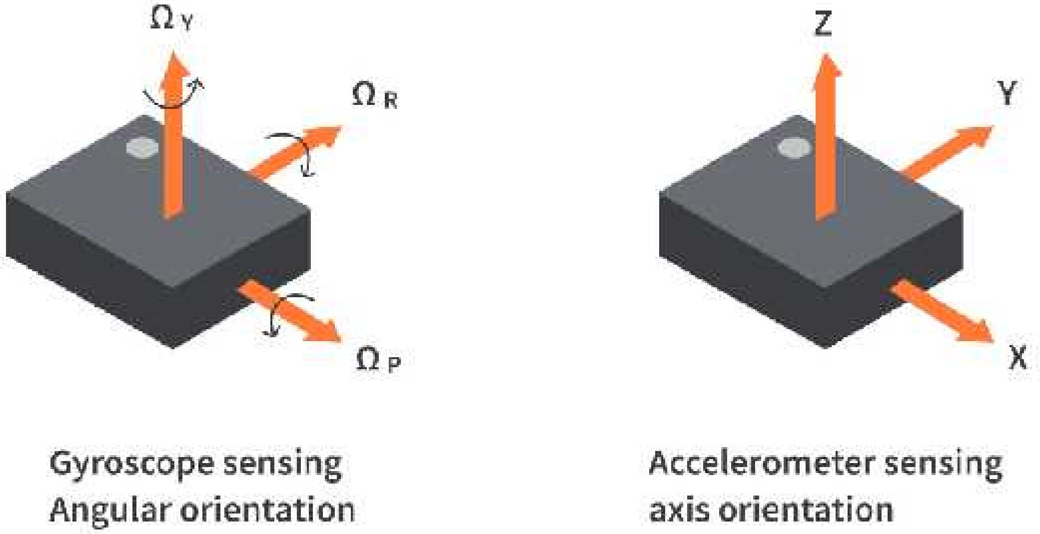


Figure 1.1 Gyroscope and accelerometer sensing operation principle

3) **Magnetometers:** Magnetometers as well one of unmanned aerial vehicle (UAV) orientation determination systems. They are used to measure the Earth’s magnetic field and assist in determining the UAV’s orientation relative to the magnetic north pole. Magnetometers provide significant information about the UAV’s heading or yaw angle.

Magnetometers measure the strength and direction of the magnetic field surrounding the UAV. By analyzing these measurements, the orientation of the UAV with respect to the Earth’s magnetic field can be determined. This information helps establish the UAV’s heading or yaw angle, which is important for navigation, orientation-based control, and position estimation.

One advantage of magnetometers is that they are not affected by external forces or accelerations, as opposed to gyroscopes and accelerometers. This makes them particularly useful for applications where the UAV needs to maintain a specific heading or orientation regardless of other forces acting upon it.

However, magnetometers are susceptible to interference from nearby magnetic sources, such as electronic components or metallic structures within the UAV itself. To reduce this interference and improve accuracy, magnetometers are often calibrated and combined with other sensor measurements using sensor fusion algorithms.

Overall, magnetometers are valuable sensors in UAV orientation systems, providing information about the Earth's magnetic field and aiding in determining the UAV's heading or yaw angle. When combined with other sensors and sensor fusion algorithms, magnetometers contribute to accurate and reliable orientation estimation, facilitating navigation, control, and position estimation for UAVs.

4) **Global Navigation Satellite Systems (GNSS):** GNSS, such as GPS (Global Positioning System), provide precise positioning and velocity information by using signals from satellites.

Is a critical component in unmanned aerial vehicle (UAV) orientation systems. While GPS is primarily used for navigation and position estimation, it also contributes to UAV orientation determination.

In UAV orientation systems, GPS receivers are commonly integrated as a part of the overall sensor set, which may include gyroscopes, accelerometers, and magnetometers. By using GPS data, the UAV can determine its geographic coordinates and velocity, which, in turn, can be used to estimate its orientation relative to the global coordinate system.

GPS works by triangulating signals received from multiple satellites to calculate the UAV's precise position and velocity. The GPS receiver measures the time it takes for the signals to travel from the satellites to the UAV, allowing it to calculate the distance between the UAV and each satellite. By combining these distance measurements from multiple satellites, the receiver can determine the UAV's position in three-dimensional space.

While GPS is primarily used for position estimation, it indirectly contributes to orientation determination. By tracking the changes in the UAV’s position over time, the GPS system can provide information about the UAV’s heading or yaw angle. By comparing the UAV’s previous and current positions, the change in heading can be estimated.

However, it’s important to note that GPS only cannot provide highly accurate and real-time orientation information, especially in situations where the UAV’s movements are get some accelerations or when GPS signals are obstructed or weak. In such cases, additional sensors like gyroscopes and accelerometers are necessary to complement GPS data and provide more immediate and accurate orientation estimation.

By combining GPS data with data from other sensors, such as gyroscopes and accelerometers, through sensor fusion algorithms like Kalman filters, the UAV’s orientation estimation can be further enhanced. Sensor combining allows you to integrate and consolidate data from multiple sensors to compensate for their respective limitations and improve the overall accuracy and reliability of UAV orientation.

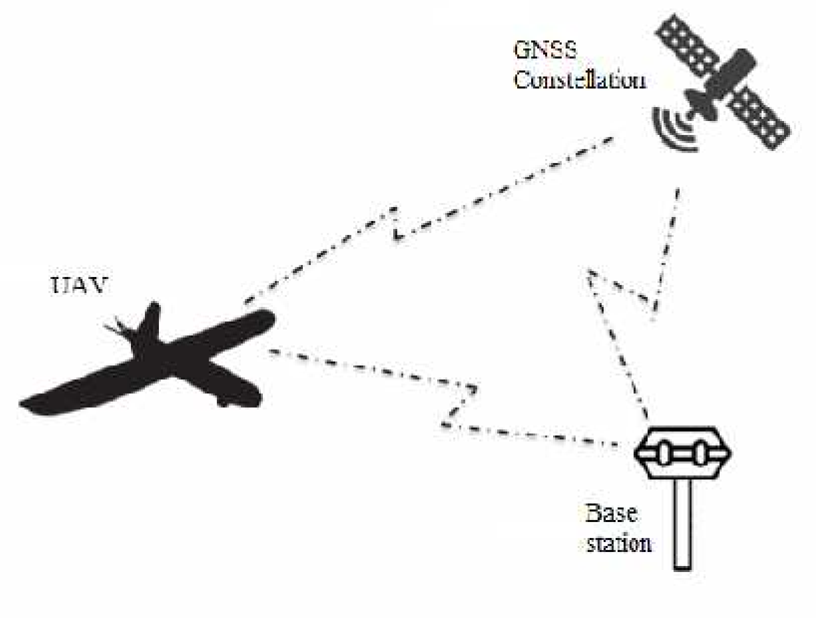


Figure 1.2 A simple scheme of the GPS system for determining the orientation of the aircraft

5) **Inertial Measurement Units (IMUs):** IMUs combine gyroscopes, accelerometers, and sometimes magnetometers into a single sensor unit. By uniting the measurements from these sensors, the UAV’s orientation can be estimated. IMUs are commonly used

in UAVs for real-time attitude estimation. However, their accuracy may degrade over time due to sensor errors and drift.

It’s important to note that different combinations and combining algorithms of these sensors can be used to enhance the accuracy, robustness, and 1reliability of UAV orientation determination systems. Additionally, advanced techniques such as sensor fusion algorithms (e.g., Kalman filtering, complementary filtering) and advanced machine learning approaches can be employed to further improve orientation estimation.

1.1Conclusion to chapter

Thus, information about the UAV’s position can be provided by different instruments and even their combination. In this part, we have reviewed some of them.

In our work, we will focus on the gyroscope and accelerometer and their combination in a complementary filter.

Because of using of gyroscopes and accelerometers individually may not be sufficient to accurately determine the UAV’s orientation, as each has its own drawbacks. The use of a complementary filter allows combining the advantages of both types of sensors, providing a more accurate and reliable orientation estimate.

Also, the option of using the CF is the most optimal in terms of “cost/quality”, since the gyroscope and accelerometer are the most affordable sensors and do not require additional equipment, unlike the GPS system.

CHAPTER 2 RESEARCH OF THE MAJOR ERROR IN WHOLE SYSTEM

2. Basic schemes of complementary filters

The complementary filter works by combining accelerometer and gyroscope measurements. The combination is performed using the filter coefficient, which determines the degree of influence of the accelerometer or gyroscope unit on the output angle.

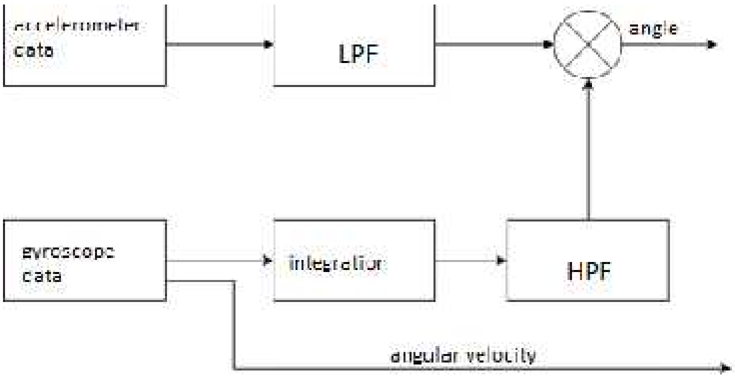


Figure 2.1 Block diagram of a digital complementary filter for MEMS gyroscope and accelerometer

The primary purpose of implementing a complementary filter is to address the zero drift issue in gyroscopes by utilizing accelerometer data. In this context, the complementary filter acts as a high-pass filter for the gyroscope and a low-pass filter for the accelerometer. Consequently, the problem is resolved in the following manner: the accelerometer readings take precedence at low frequencies, effectively eliminating zero drift, while the gyroscope readings dominate at high frequencies.

Complementary filters are usually created using two schemes:

- Filtering scheme
- Compensation scheme.

2.1 Analysis of the complementary filter created by filtering scheme

The purpose of the analysis is to study the effect of linear accelerations on the accuracy of a complementary filter and to select the filtering structure from this point of view.

Currently, to measure the angular position of an object, the complementary filter scheme shown in Fig.2.2 is most often used.

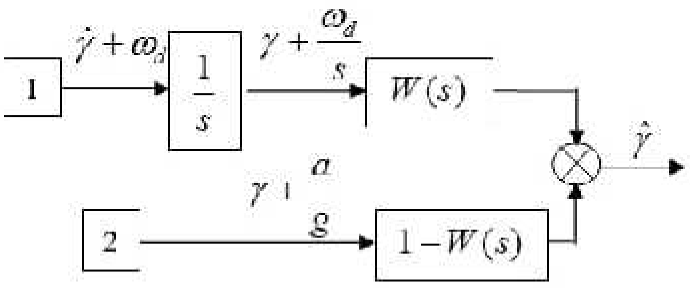


Figure 2.2 A filtering scheme of CF

Where, 1 – gyroscope (angular velocity sensor); 2 – accelerometer; ¥ - object rotation angle; ¥̂ - output signal; ω_d - angular drift rate of the gyro; a - object acceleration

Given, $W(s)\,\text{X}\frac{s}{Ts\,\Gamma 1}$ the following scheme will be as at figure 6. So, we have first order component in our case.

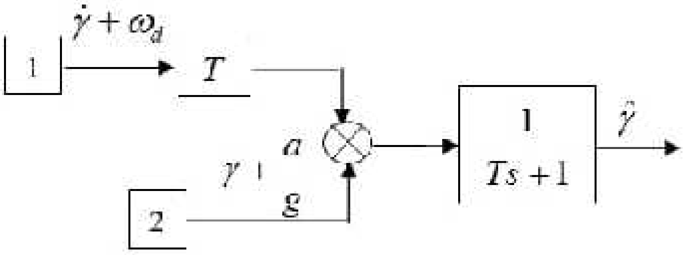


Figure 2.3 First order CF by filtering scheme

Let’s write down the expression for the filter error

$$\text{¢ X}\frac{T}{Ts\,\Gamma 1}\mu_d\,\Gamma\frac{1}{Ts\,\Gamma 1}\frac{a(t,^2)}{g} \qquad (1)$$

Let’s assume that there is a constant acceleration over a short period of time ² (several seconds)

$$a(t,^2)\,\text{X}\begin{matrix} a, & t\ \text{™}^2 \\ 0. & t\ \Psi^2 \end{matrix}\ \text{X}a(t)\,\text{Z}a(t\,\text{Z}^2)$$

Then, the second component of expression (1) can be written as follows

$$\text{¢}_2\,ƒt,^2\,\text{ÅX}\frac{a}{g}\ 1\text{Z}e^{\text{Z}\frac{t}{T}}\ \ \text{Z}\frac{a}{g}\ 1\text{Z}e^{\text{Z}\frac{t\text{Z}^2}{T}}\ \ \text{X}\frac{a}{g}e^{\text{Z}\frac{t}{T}}\ \ e^{\frac{^2}{T}}\,\text{Z}1 \qquad (2)$$

For short-term disturbance (τ less than T) we have $e^{-\frac{\tau}{T}} \approx 1+\frac{\tau}{T}$, so

$$\Delta_2(t,\tau)=\frac{a}{g}\frac{\tau}{T}e^{-\frac{t}{T}}$$

To reduce its influence, the time constant T of the aperiodic part should be much larger than the time interval τ.

Formula (2) can be written as

$$\Delta_2(t,\tau)=\frac{a}{g}\frac{\tau}{T}e^{-\frac{t}{T}}=\tau\frac{d}{dt}\;\frac{a}{g}\;1-e^{-\frac{t}{T}}\quad=\tau\dot{\Delta}_2(t) \tag{3}$$

Summarise,

$$f(t,\tau)=f(t)-f(t-\tau)=\tau\frac{f(t)-f(t-\tau)}{\tau}\approx\tau\dot{f}(t) \tag{4}$$

We can write down

$$\Delta=\frac{T}{Ts+1}\omega_d+\frac{s}{Ts+1}\tau\frac{a}{g} \tag{5}$$

We have

$$\Delta_{t=0}=\frac{\tau}{T}\frac{a}{g};\ \Delta_{t\to\infty}\approx T\omega_d \tag{6}$$

Error $\Delta_{t=0}$ is maximal filter error

Estimate the filter errors. For $\frac{a}{g}=1$, accelerometer error will be $arctg(1)=45^0$.

Consider $\tau=5c; T=100c;\ \omega_\partial=5\;10^{-5}1/c$

We get $\Delta_{t=0}=\frac{a}{g}\frac{\tau}{T}=2,87^0$.

Static error due to gyroscope drift is equal to $\Delta_{t\to\infty}=T\omega_d=0,29^0$

The simulation results are shown in Figure 7. The maximum error can be reduced by increasing the time constant T. However, this increases the steady-state error due to gyroscope drift. Let us take the notation in the figure as:

Dashed line “- - -“ is the error due to gyroscope drift; dotted line “- · - · -“ is the error due to acceleration; solid line “—” is the total error). In the following figures we will use the same notation

For T =200s , the simulation results are shown in Figure 2.5

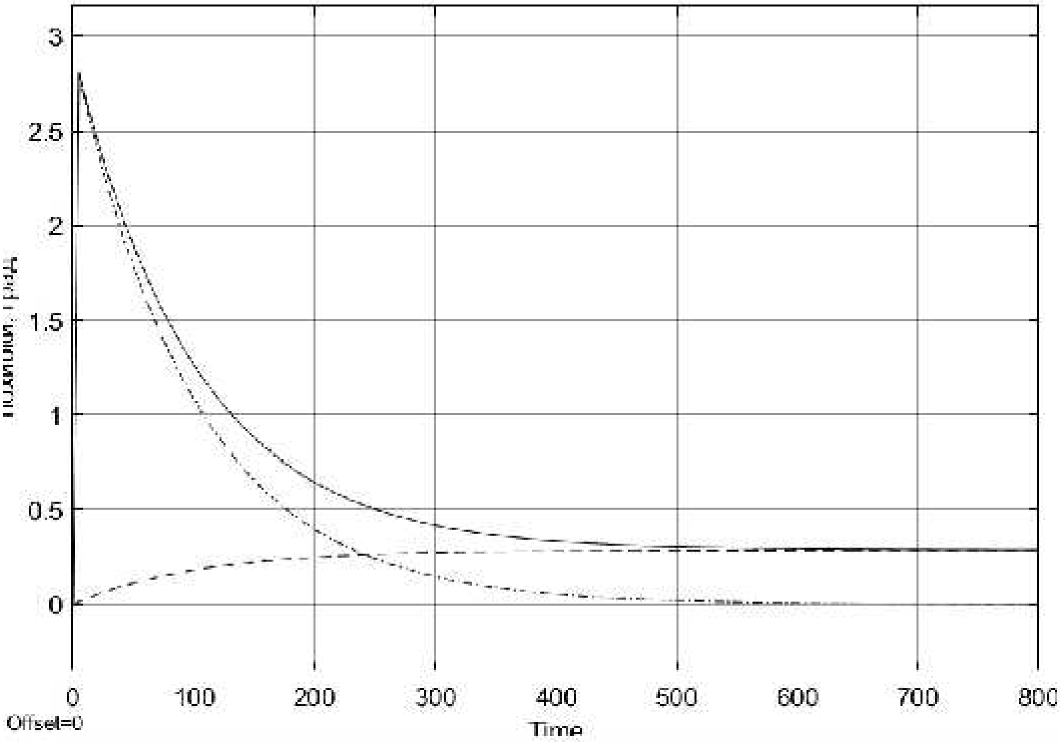


Figure 2.4 Simulation result of first order CF for T=100s

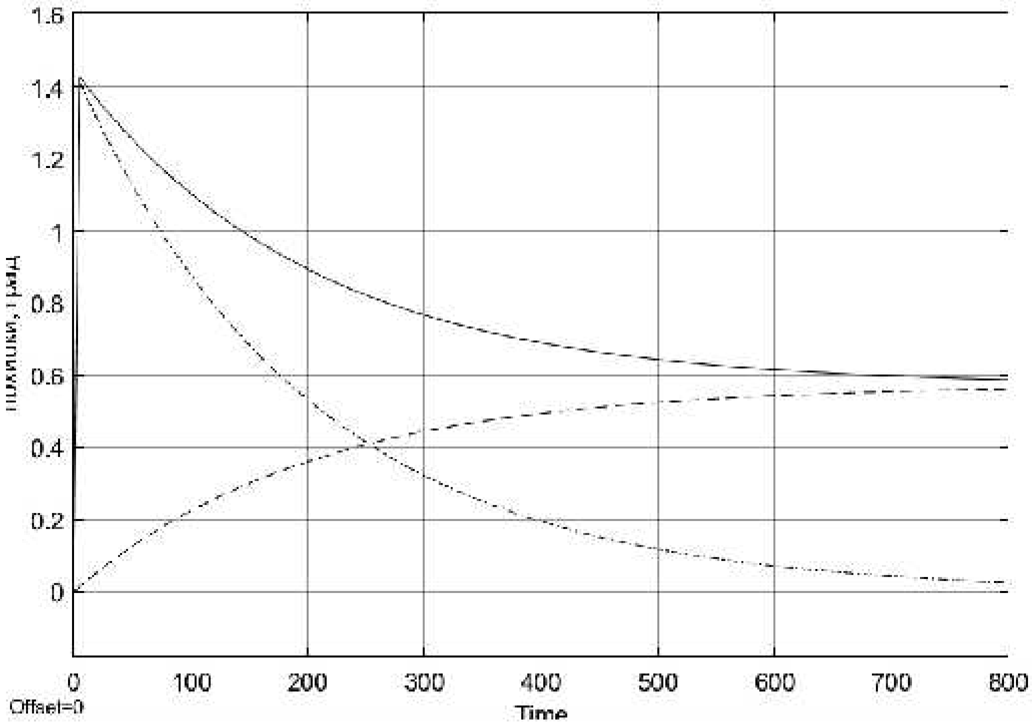


Figure 2.5 Simulation result of first order CF for T=200s

Consider using a second-order filter

$$W(s)\,\mathrm{X}\frac{s^2\,\Gamma r_1 s}{s^2\,\Gamma r_1 s\,\Gamma r_2};\ 1\,\mathrm{Z}W(s)\,\mathrm{X}\frac{r_2}{s^2\,\Gamma r_1 s\,\Gamma r_2};$$

The following scheme will be as at figure 9.

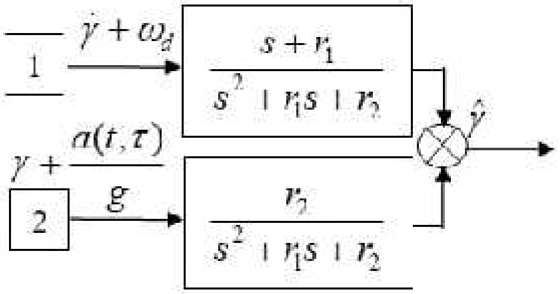


Figure 2.6 Second order CF for filtering scheme

Let’s write down the expression for the filter error

$$¢\ \mathrm{X}\frac{s\,\Gamma r_1}{s^2\,\Gamma r_1 s\,\Gamma r_2}\mu_d\,\Gamma\frac{r_2}{s^2\,\Gamma r_1 s\,\Gamma r_2}\frac{a(t,²)}{g} \qquad (7)$$

Taking into account (6), replace $a(t,²)$ to $s² a$, we receive

$$¢\ \mathrm{X}\frac{s\,\Gamma r_1}{s^2\,\Gamma r_1 s\,\Gamma r_2}\mu_d\,\Gamma\frac{r_2}{s^2\,\Gamma r_1 s\,\Gamma r_2}s²\,\frac{a}{g}\,\mathrm{X}\frac{1}{s^2\,\Gamma r_1 s\,\Gamma r_2}\quad \mu_d\,\Gamma r_2²\,\frac{a}{g}\ \ s\,\Gamma r_1\mu_d \qquad (8)$$

From these expressions we can see:

$$¢_{tX0}\ X0;\ ¢_{t|}\ _{|}\ |\quad \frac{r_1}{r_2}\mu_d \tag{9}$$

Lets take r_1 X3 $10^{Z2}, c^{Z1}$; r_2 X1 10^{Z4}. The modelling results are shown in the figure 10.

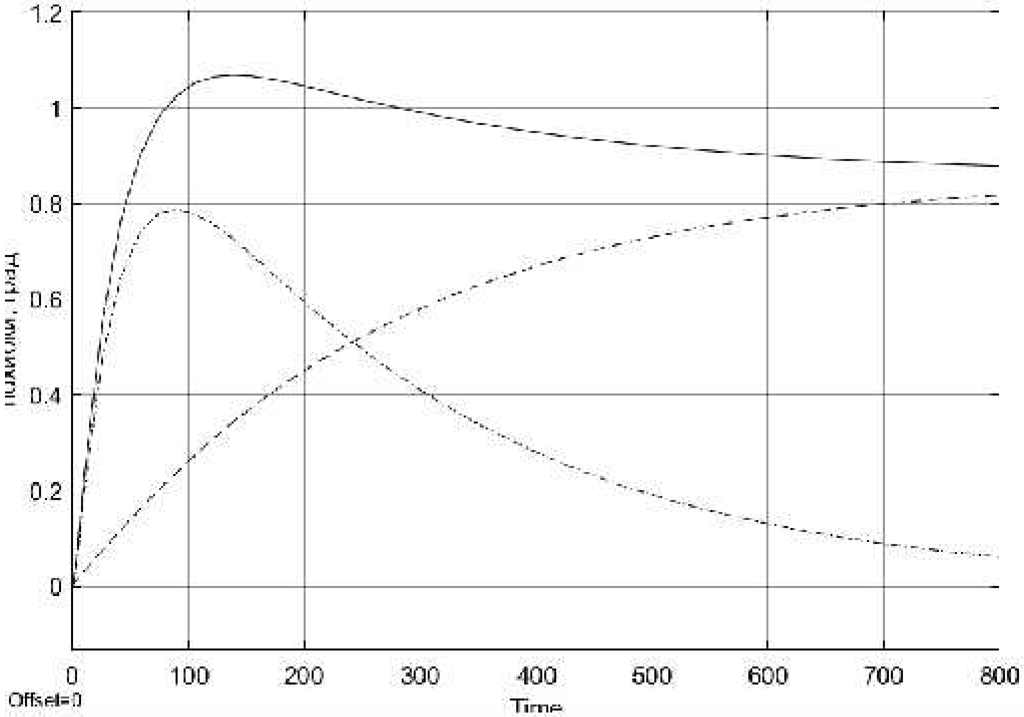


Figure 2.7 Simulation result for second order CF in filtering scheme

Comparing Fig. 2.4 and Fig. 2.7, we can see that the results are quite close. That is, the use of a more complex second-order filter to improve the accuracy of the readings for the accepted interference parameters is not appropriate.

We will consider the compensation scheme in the next chapter, as it is the compensation method that is best designed to solve the problem of linear acceleration.

One of the main advantages of the compensation scheme is that we can extract only the difference signal, while leaving the useful signal unchanged. Working with this method, we can estimate only the error without using additional elements.

2.2 The main errors of the sensing elements included in complementary filters

Achieving high measurement accuracy when using complementary filters necessitates careful consideration of various factors. The primary issues that directly impact measurement accuracy are as follows:

1) Influence of high-frequency interference: High-frequency interference can introduce errors in the measurements. However, this problem has been addressed in

existing solutions. To mitigate the impact of high-frequency interference, the complementary filter circuit removes the gyroscope signal integration operation, as described in publications [3, 9].

2) Influence of accelerometer and angular velocity sensor errors: The accuracy of the measurements can be affected by errors in the accelerometer and angular velocity sensors. Minimizing these errors is crucial for improving measurement accuracy.

3) Choice of measurement parameters: Selecting appropriate measurement parameters is essential for optimizing accuracy. Factors such as sampling rate, sensor calibration, and filter coefficients need to be carefully considered.

By analyzing existing solutions, it has been determined that the issue of high-frequency interference can be effectively mitigated by eliminating the gyroscope signal integration operation in the complementary filter circuit, as outlined in publications [3, 9].

Publication [5] reviewed the impact of accelerometer errors and presents three methods aimed at reducing medium and low-frequency errors:

a) Increasing the filter coefficient: By adjusting the filter coefficient, the influence of accelerometer errors can be minimized. Increasing the coefficient helps to attenuate the error signals effectively.

b) Positioning the sensor close to the axis of rotation: Placing the accelerometer sensor as close as possible to the object’s axis of rotation helps reduce error rates. This proximity minimizes any external disturbances or inaccuracies introduced during the measurement process.

c) Modifying the filter’s output scheme: Altering the filter’s output scheme can lead to an improved frequency response, thereby reducing errors in the medium and low-frequency range.

It is important to note that one of the significant errors associated with accelerometers is the impact of linear accelerations. These linear accelerations can introduce inaccuracies in the accelerometer readings, and addressing this error source is crucial for achieving accurate measurements.

2.3 The effect of linear accelerations on sensitive elements

The influence of linear accelerations plays a significant role in the calculation of the complementary filter (CF) error. These accelerations have an impulsive nature and can introduce second or third-order errors, thereby greatly impacting the overall error value.

Now, let’s examine the effect of accelerations resulting from acceleration, deceleration, and object rotation on the accuracy of the complementary filter. We can express the filter error as follows:

$$\delta = \frac{T}{T \quad +1}\delta_1 + \frac{T}{T \quad +1}\delta_2$$

Consider the filtering scheme of complementary filter.

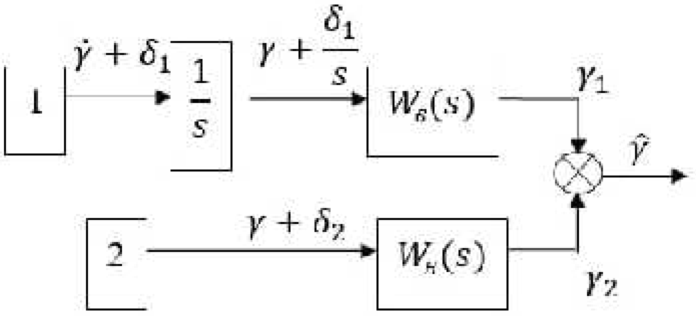


Figure 2.8 Scheme of complementary filter

In Figure 2.8: 1 - angular velocity sensor (AVS), 2 - accelerometer sensor; ↑- object rotation angle; δ_1, δ_2- interferences; $W_в$(s), $W_н$ (s) - transfer functions of high-frequency and low-frequency interferences; ¥ - output signal.

Let’s take

$$W_в(s) = \frac{s^2 + r_1 s}{s^2 + r_1 s + r_2}; W_н(s) = \frac{r_2}{s^2 + r_1 s + r_2}$$

Then

$$\delta = \delta_1 \frac{s + r_1}{s^2 + r_1 s + r_2} + \delta_2 \frac{r_2}{s^2 + r_1 s + r_2}$$

We can see that there is no integration operation of the gyroscope signal. The static value of the error from the gyroscope zero offset $\delta_1 = \omega_д$ is equal to

$$\delta_{\omega_д} = \frac{r_1}{t_2}\omega_д$$

Based on the initial calculations, it becomes evident that linear accelerations resulting from object acceleration, deceleration, and turning, with durations longer than

1 second, introduce significant second or even third-order errors. These errors have a substantial impact on the overall error value of the complementary filter (CF). So, there is a need to develop methods that effectively reduce the influence of linear acceleration on CF accuracy.

One well-known method involves temporarily disabling the accelerometer during sudden accelerations. Since the angle deviation is relatively slow during these periods, turning off the accelerometer for a brief duration allows its error to be neglected. In this case, the angle estimation is solely based on gyroscope readings. However, this method necessitates the use of additional equipment.

Another approach is to combine the complementary filter with GPS data. The proposed algorithm involves calculating accelerations by double differentiating the coordinates obtained from GPS and then subtracting them from the accelerometer output signals. This method used GPS data to compensate for accelerometer errors induced by linear accelerations.

Consequently, that both of these methods require the utilization of supplementary equipment. Thus, the problem of reducing accelerometer errors caused by linear accelerations using solely the components of the complementary filter remains unresolved.

2.4 Static and dynamic models of a complementary filter

In order to study the accuracy of a complementary filter (CF) on both stationary and moving bases, it is important to consider different models of CF operation.

The static model refers to a mode of operation where the tilt angles of a moving object (MO) remain constant over time, and there are no linear accelerations of the MO. This means that the MO can either be stationary (not moving) or moving at a constant speed. In this case, the accuracy is primarily determined by sensor errors, such as those of the gyroscope and accelerometer. Consequently, the main source of error is the inaccuracy of these sensors.

On the other hand, the dynamic model represents a mathematical model of the orientation system with a complementary filter, considering time-varying angles of inclination of the MO and the presence of linear accelerations. When the MO is in motion, additional factors appears, that can impact accuracy. Vibration is one such factor that can lead to inaccurate measurements. Moreover, linear accelerations resulting from various movements, speed changes, and other factors can also affect the accuracy of orientation determination on a moving base.

To analyze the influence of errors and factors affecting accuracy, a diagram can be constructed.

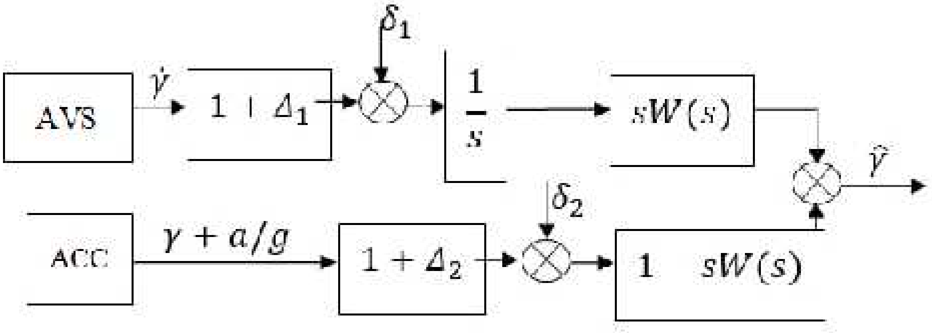


Figure 2.9 Block diagram of the CF

In Figure 2.9: AVS - angular velocity sensor; ACC - accelerometer sensor; ↑- object rotation angle; a - linear acceleration of the object; Δ_1, Δ_2 - errors of the AVS and ACC transmission coefficients correspondingly; δ_1, δ_2- interferences at the outputs of the AVS and ACC correspondingly. Linear acceleration in this scheme is considered in terms of accelerometer interference.

The output signal of the system ¥ is equal:

$$¥ = [s\ \ (1+\Delta_1)+\delta_1]\frac{1}{s}s \quad + \left(\left(\gamma+\frac{a}{g}\right)(1+\Delta_2)+\delta_2\right)(1-s \quad) \approx$$

$$\approx \gamma + \frac{a}{g}(1-s \quad) + \gamma\Delta_1 s \quad + \delta_1 W + (\gamma\Delta_2+\delta_2)(1-s \quad) =$$

$$= \gamma + \frac{a}{g}(1-s \quad) + \Delta_1\gamma s \quad + \Delta_2\gamma(1-s \quad) + \delta_1 W + \delta_2(1-s \quad).$$

The system error is equal:

$$\delta = \hat{\gamma} - \gamma = \frac{a}{g}(1-s \quad) + \Delta_1\gamma s \quad + \Delta_2\gamma(1-s \quad) + \delta_1 W + \delta_2(1-s \quad)$$

It should be noted that the component $\frac{a}{g}(1-s \quad)$,

where a - acceleration, g - gravitational acceleration and sW is gyroscope error, is the result of the measurement process itself and is therefore a methodological error. This component is caused by the interaction of non-ideal sensors, such as a gyroscope, with the physical quantities being measured.

Depending on the quality and calibration of the measuring equipment, the methodological error can vary. It can be caused by various factors, such as noise, sensor instability, nonlinearity of the instruments, etc. Thus, this methodological error affects the accuracy of orientation determination and must be taken into account when processing measurements and performing accuracy assessment, but anyway this value does not have the same impact as dynamic error.

2.5 Problem statement

The analysis showed that the topic of the effect of linear accelerations on the accuracy of complementary filter calculations is not fully developed. Therefore, it is relevant to develop a method of compensating for linear accelerations that affect the accuracy of the measured parameters.

To solve this problem, it is necessary to consider and verify the fulfilment of the conditions for both types of schemes of the complementary filter construction.

It is necessary to select the following parameters of the gyroscope and accelerometer that would reduce the measurement error caused by the influence of accelerations

It is necessary to analyse the static and dynamic errors of the complementary filter in order to evaluate and separate the clear effect of accelerations. The proposed method should also include the solution of high-frequency interference problems.

To evaluate the result, MatLab and Simulink environments will be used to show that the specified conditions are satisfied.

The complementary filter must satisfy the following requirements:

- Angle variation range - ±200^0.

Measurement errors on a fixed base:

- on a horizontal base, no more than ±28.8 degrees per minute;
- when measuring angles ±150, no more than ±60 degrees per minute.

Measurement accuracy ± 90 degrees per minute at:

- multiple impacts (amplitude 15g, duration 10-15 ms, number of impacts 60, frequency 80 impacts per min);
- sinusoidal vibration in the frequency range from 20 to 120 Hz with an amplitude of 6g.

2.6 Selecting the structure and parameters of the transfer function

To analyse the impact of errors, we firstly consider the choice of the structure and parameters of the transfer function (TF).

In the calculations, we assume that the moving object is moving at a speed of 90 km/h, which is 25 m/s, and the duration of the movement is 5 seconds. The value of the gyroscope zero offset is approximately 10°/h.

Using this data, we can take into account the effect of errors and estimate the accuracy of measuring the object’s orientation.

At the initial stage of the analysis, the structure of the transfer function (TF) was chosen - a second-order oscillatory unit.

$$W_1(s) = \frac{s^2 + r_1 s}{s^2 + r_1 s + r_2};\ W_2(s) = \frac{r_2}{s^2 + r_1 s + r_2}$$

System properties: The parameters r_1 and r_2 in the transfer function may represent system-specific properties such as damping, resonance, or natural frequency. The selection of these parameters depends on the desired response of the system and the characteristics of the sensors and actuators used.

By utilizing modeling techniques, the parameters of the transfer function were selected based on the accepted calculation parameters. Using the Simulink environment, we will construct the corresponding schematic of a complementary filter.

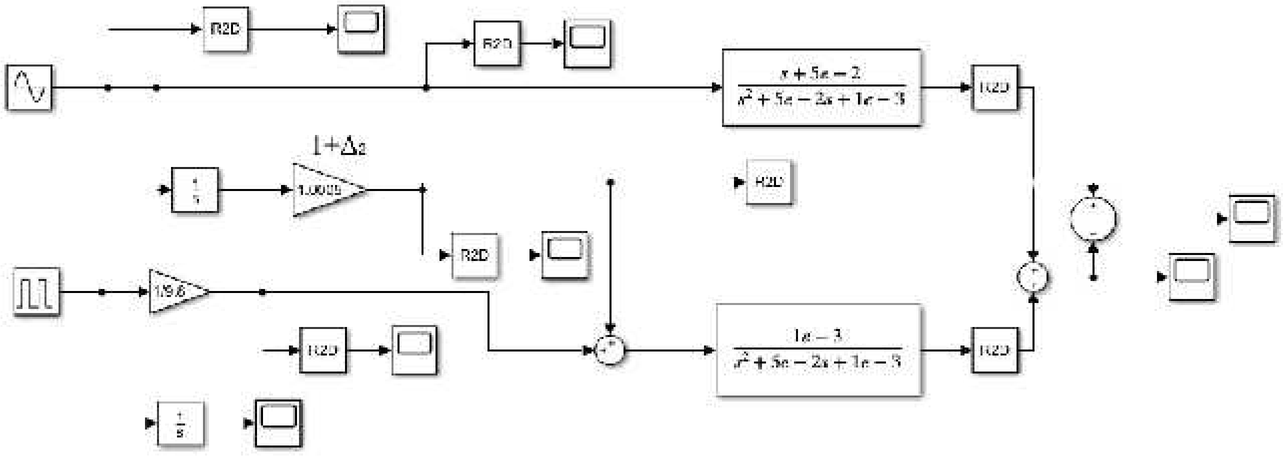


Figure 2.10 The CF scheme for estimating the transfer function in Simulink environment

In this scheme, the sinusoidal signal (sine wave block) simulates the operation of the angular velocity sensor, and the pulse signal (pulse generator block) simulates the operation of the accelerometer. In accordance with Figure 2.8, the transfer functions of the AVS and ACC signals were developed.

Let's run this model and analyse the resulting graph to verify the scheme is working correctly. We can also estimate the values of the transfer functions to ensure the desired accuracy and transient time.

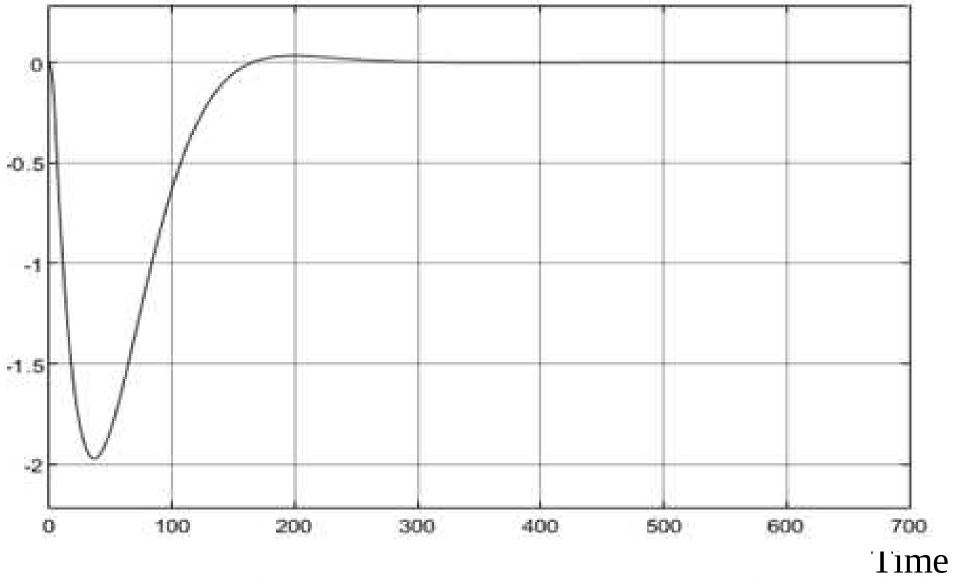


Figure 2.11 The result of modelling CF scheme to estimation of the transfer function

According to the data obtained, we can see that the transfer function is chosen correctly and is close to the required accuracy margin. However, we can see that it is necessary to reduce the transient time as it is 300 seconds, which exceeds the required parameters. It is also necessary to reduce the error by approaching its value to 1˚. To do this, in the following sections, we will conduct a more accurate analysis and refinement of the parameters for different CF models.

2.7 Effect of errors in the static CF model

Since we use both an angular velocity sensor and accelerometer, both static and dynamic errors are involved in the measurements. The static errors are caused by the operation of the AVS, and the dynamic errors are caused by the accelerometer action.

Let us consider in more detail the influence of errors in the static model. To do this, we need to exclude dynamic errors from Figure 2.3. We get the following diagram:

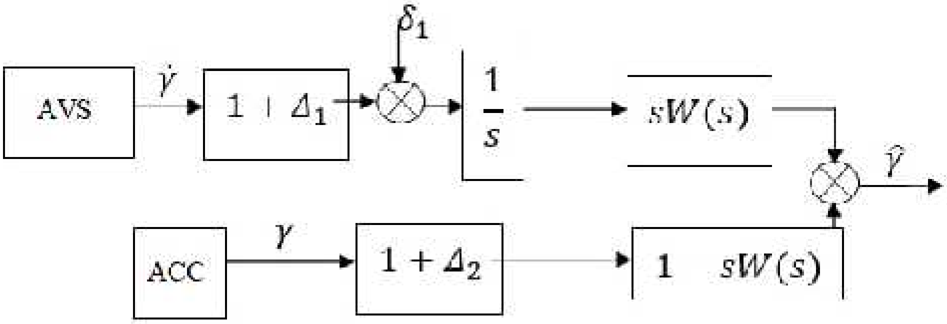


Figure 2.12 Block diagram of the static complementary filter model

The diagram in Figure 2.12 is similar to Figure 2.9, but the dynamic error component is removed.

Since the gyroscope zero offset (gyro drift) is a passport value, its influence will exist in the static model as well.

The output signal will look like this:

$$\hat{\text{¥}} = [s \ (1+\Delta_1)+\delta_1]\frac{1}{s}s \quad + \big(\text{¥}(1+\Delta_2)\big)(1-s \quad) \approx$$
$$\approx \gamma + \gamma\Delta_1 s \quad + \delta_1 W + \gamma\Delta_2(1-s \quad) =$$
$$= \gamma + \Delta_1\gamma s \quad + \Delta_2\gamma(1-s \quad) + \delta_1 W$$

And the error of the whole system will be:

$$\delta = \hat{\text{¥}} - \text{¥} = \delta = \hat{\gamma} - \gamma = \Delta_1\gamma s \quad + \Delta_2\gamma(1-s \quad) + \delta_1 W$$

To visualise the effect of errors in a static complementary filter model, we can develop a simplified diagram. In this scheme, we will exclude the dynamic component and use the Delay function to stop the rotation at 10°. The transient time will be determined by the natural frequency.

The obtained scheme will look as follows:

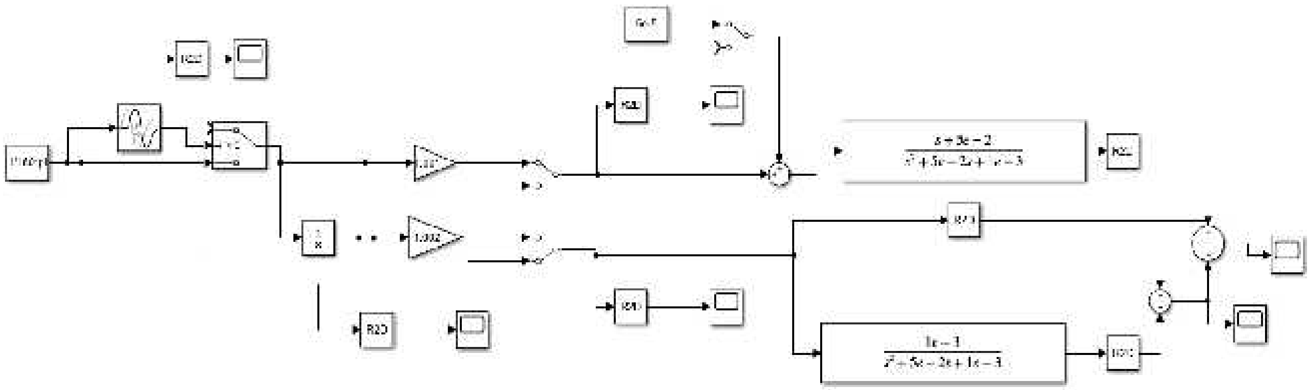


Figure 2.13 General scheme of a static model

Let’s check that the condition of tilting the body by 10˚ is fulfilled. We get the following result.

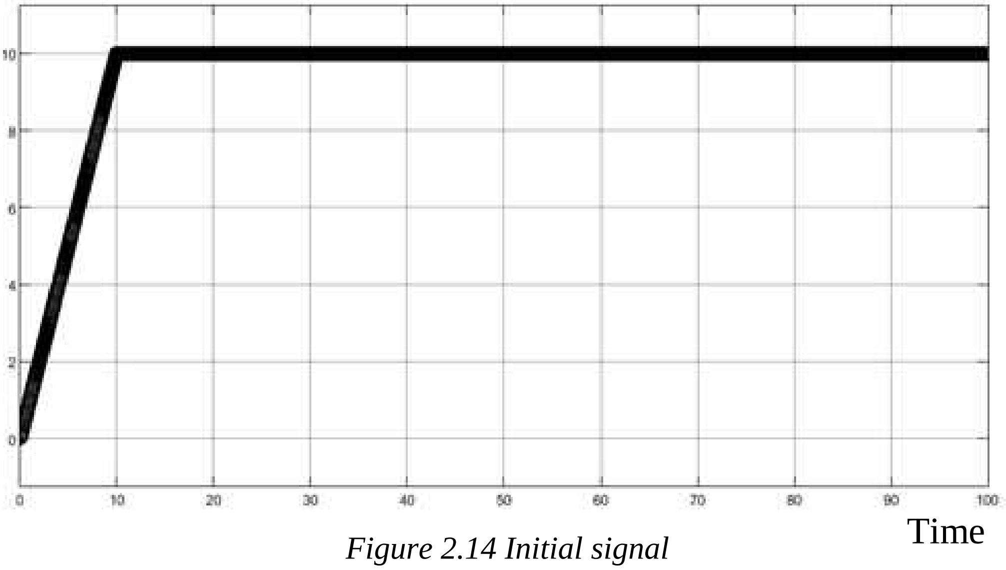


Figure 2.14 Initial signal

Let us consider the influence of the coefficients K1 and K2 on the output error of the system.

Consider individually the error of the coefficient K1 in the AVS. To do this, turn off the influence of other coefficients using the switches

We will get the following signal:

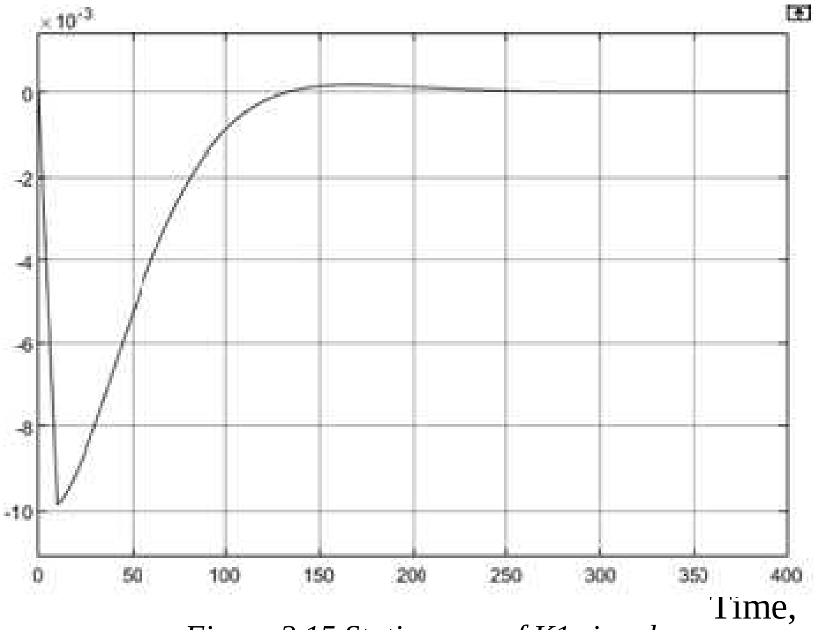


Figure 2.15 Static error of K1 signal

The error of the K1 coefficient is $10^{-3\circ}$, which is only 1 percent of the total error. Similarly, consider the effect of the accelerometer’s K2 coefficient.

We will get the following result:

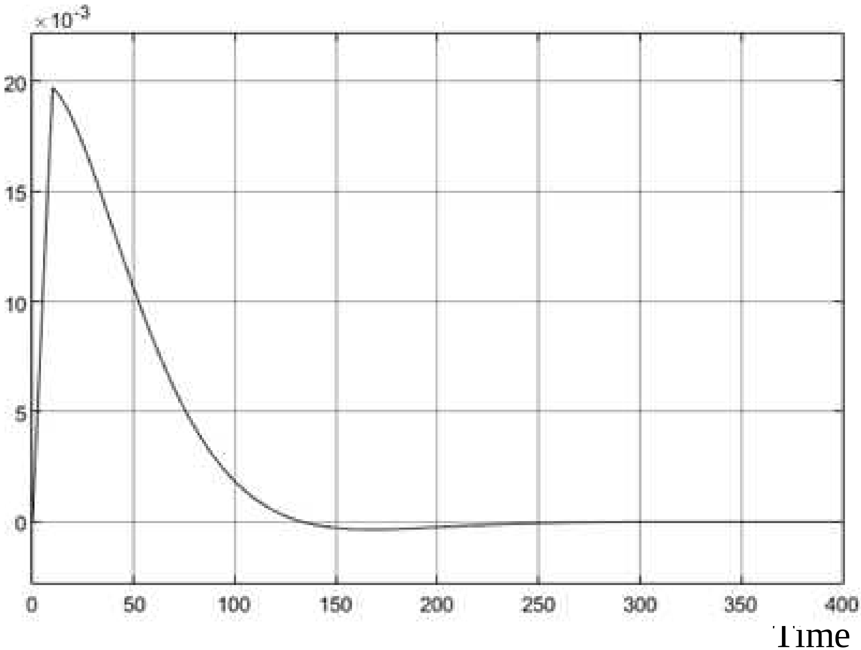


Figure 2.16 Static error of K2 signal

The error value of the K2 coefficient as well is $10^{-3\circ}$, which is 1 percent of the total error.

We can see that the influence of the K1 and K2 coefficients is almost the same.

It is also necessary to simulate the zero displacement offset error of angular velosity sensor. Its output signal will have the following form:

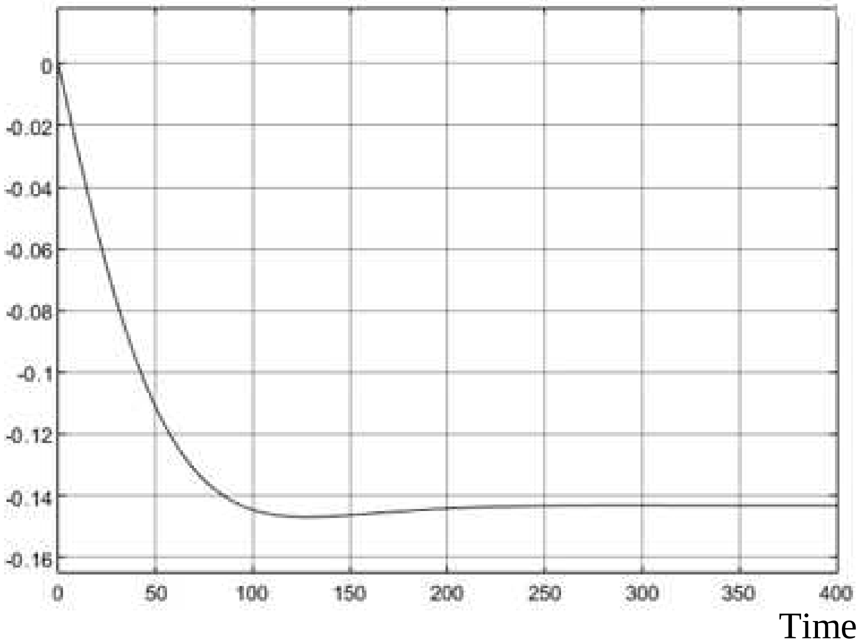


Figure 2.17 Zero offset error signal

The value of the zero offset error is the largest among the static errors and reaches a value of -143*10^{-2}°. The influence of the zero offset error is 14.5 percent of the desired total error of 1˚, which is an acceptable value.

2.8 Effect of errors in the dynamic CF model

Let's take a more detailed analysis of the effect of errors in a dynamic model. The following diagram shows this process:

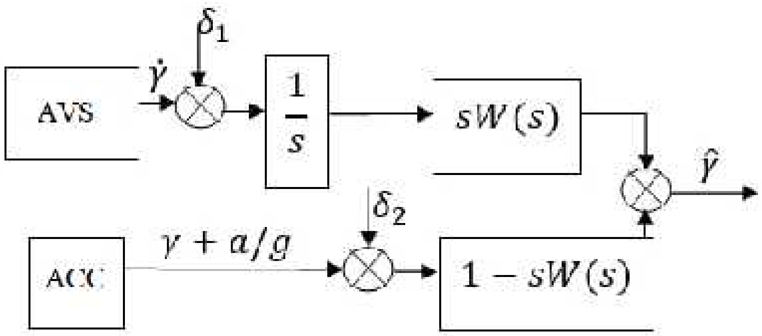


Figure 2.18 Block diagram of the dynamic CF model

Let's write down the output signal of this scheme:

$$\text{¥} = [s \quad + \delta_1]\frac{1}{s}s \quad + \left(\left(\gamma + \frac{a}{g}\right) + \delta_2\right)(1 - s \quad) \approx$$

$$\approx \gamma + \frac{a}{g}(1 - s \quad) + \delta_1 W + \delta_2(1 - s \quad)$$

The system error is equal:

$$\delta = \hat{\gamma} - \gamma = \frac{a}{g}(1 - s \quad) + \delta_1 W + \delta_2(1 - s \quad)$$

According to the calculations made earlier, we set the speed of the object to 25 m/s and the duration at 5 seconds. To simulate this speed, we will use the Pulse generator block in Simulink.

Let’s check that the specified parameters for this unit are fulfilled:

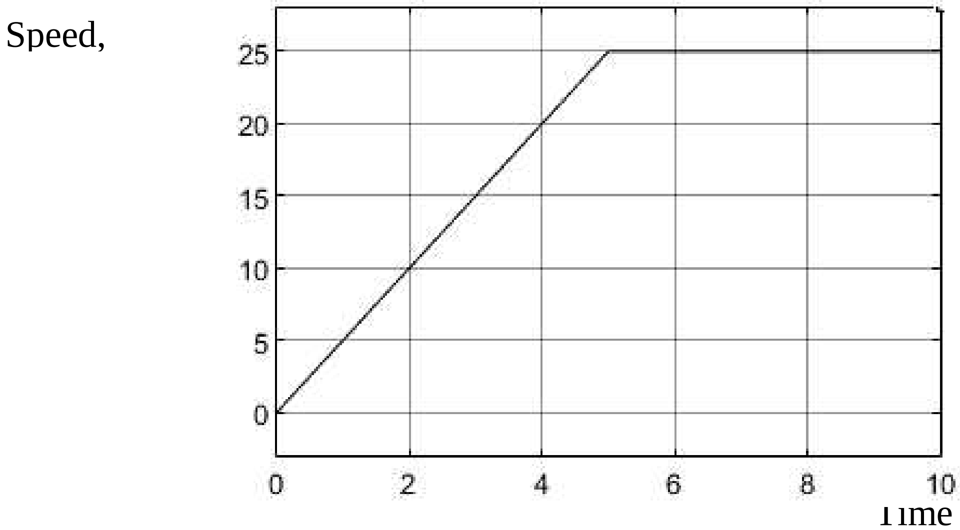


Figure 2.19 Object velocity value

Based on the results, we can see that the parameters are correctly set, and the speed reaches a value of 25 m/s in 5 seconds.

In addition to the impulse, there is also interference from the accelerometer itself. We can model the interference of the accelerometer as a harmonic oscillation and add it to the static scheme.

Let’s show the harmonic oscillations on the diagram and incorporate them into the static scheme.

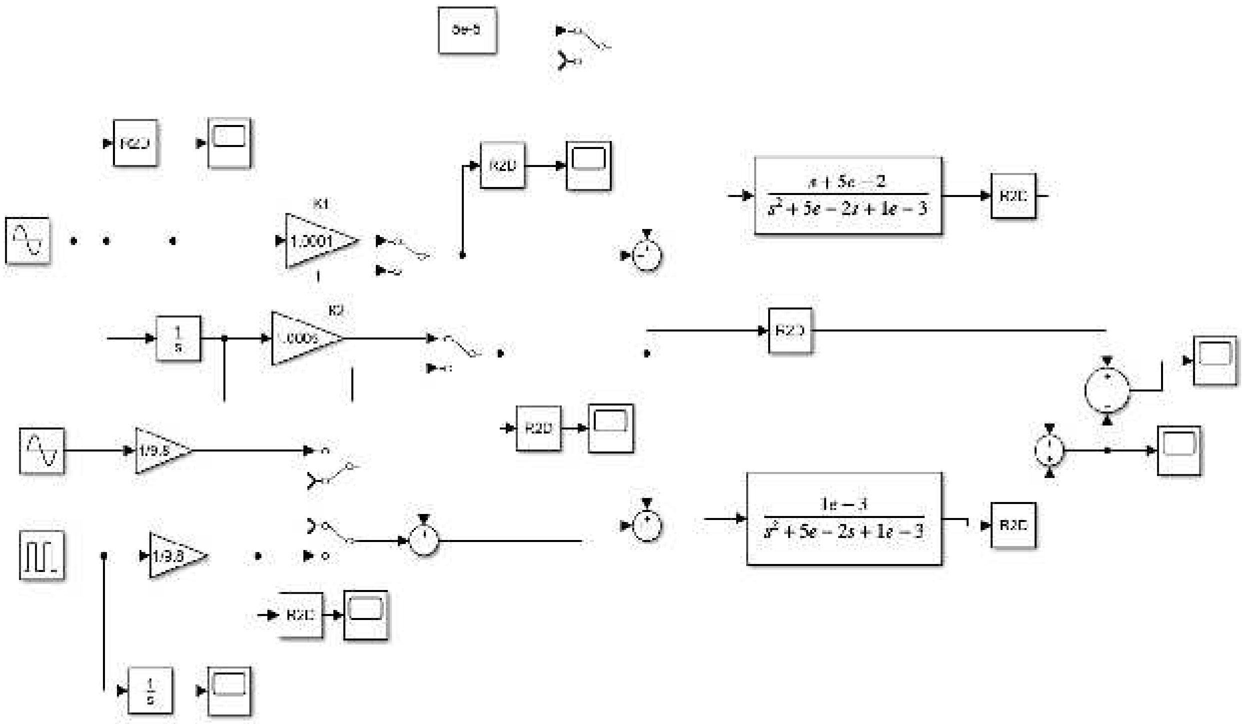


Figure 2.20 Scheme of simulation of the dynamic model of the CF

Let’s consider the effect of accelerometer vibrations and impulse on the system error separately.

By keeping only the influence of accelerometer vibration enabled, we obtain the following error readings.

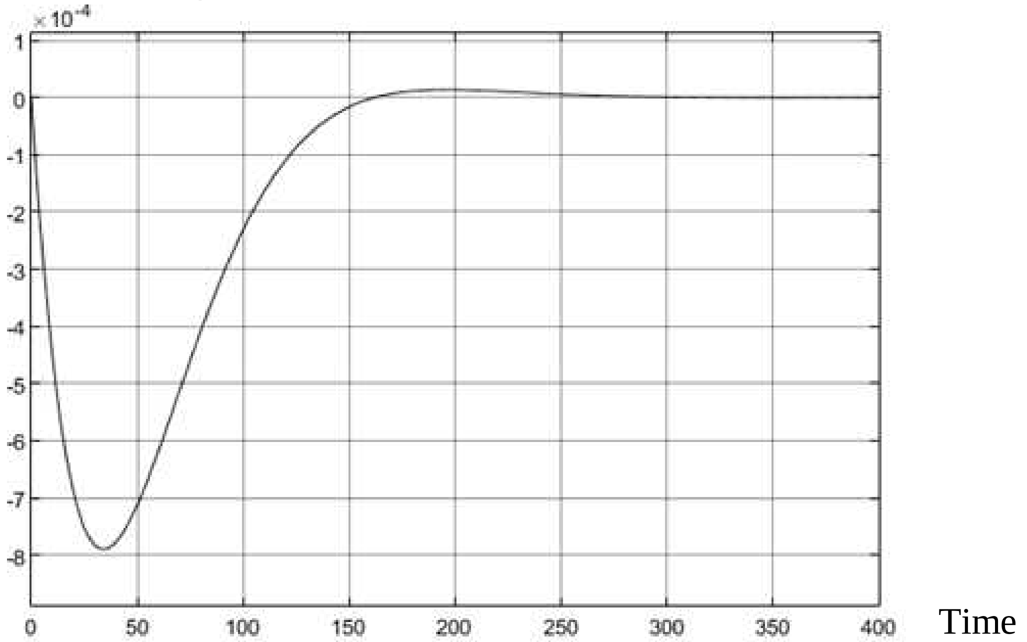


Figure 2.21 ACC dynamic error signal, ACC vibration

The error value due to vibration force is $10^{-4\circ}$.

By keeping only the influence of linear acceleration enabled, we obtain the following error readings.

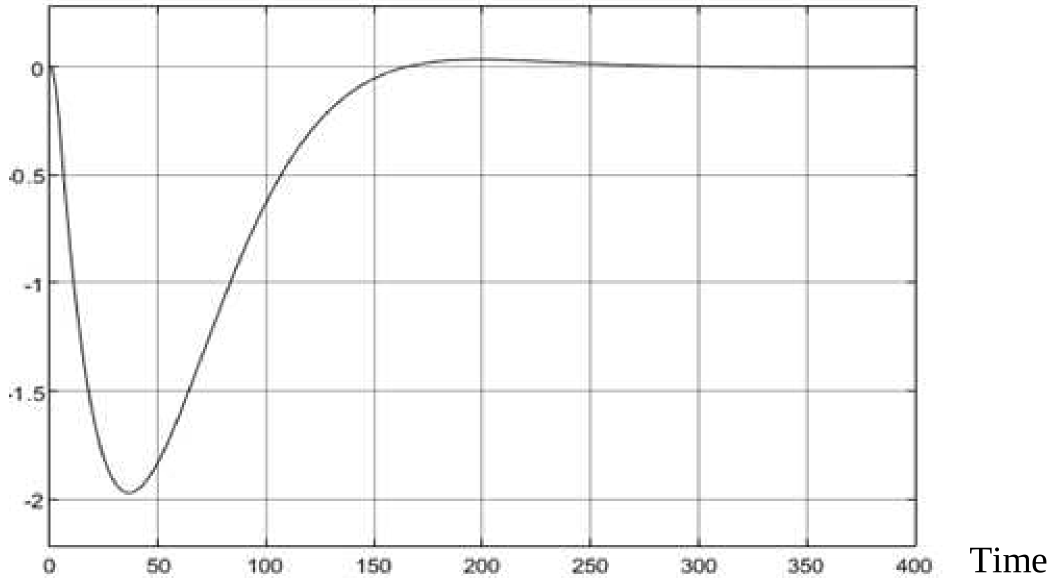


Figure 2.22 ACC dynamic error signal, ACC linear acceleration

The graph shows that the setup time exceeds 300 seconds, and the dynamic component of the error is higher for 2-3 orders of magnitude than the static component. The influence of linear acceleration exceeds the zero displacement offset error at several times, and almost reaches 2˚ which is 200 percent error from acceptable 1˚. Its means that in the further development it is necessary to focus on reducing the influence of acceleration.

2.9 Conclusion to chapter

In this section, we have considered the filtering scheme of the complementary filter and concluded that the use of a second-order filter is not reasonable, since the result is almost the same as the first-order filter.

The main causes of the error of the complementary filter and the accelerometer itself were also discovered through the literature analysis.

The static and dynamic models of the CF were considered, and as a result, the static error is caused only by the methodological error of the sensors, while in the dynamic model, vibrations and accelerations create interference, exceeding the permissible error by 200 percent in our case.

Thus, it is reasonable to consider in more detail the effect of acceleration and the operation of the accelerometer. It is necessary to reduce the transient time, as well as to reduce the value of the dynamic component error. These requirements can be achieved by choosing the most optimal the structure and parameters of the dynamic model.

So, in the future, we will find solutions to compensate for the acceleration of the moving object, as this is the largest component of the overall system error.

CHAPTER 3 DEVELOPMENT OF A METHOD FOR COMPENSATING A LINEAR ACCELERATIONS

3.Dynamic parameters of the CF error according to the compensation scheme

When analyzing the complementary filter scheme, it is important to focus on the dynamic errors of the system. In this case, the linear accelerations have the greatest impact on the output of the complementary filter, which represents a dynamic measurement error. To reduce the influence of these errors, we will apply a compensation scheme in the design of the complementary filter.

Let's consider a complementary filter based on the compensation scheme in general (Figure 3.1).

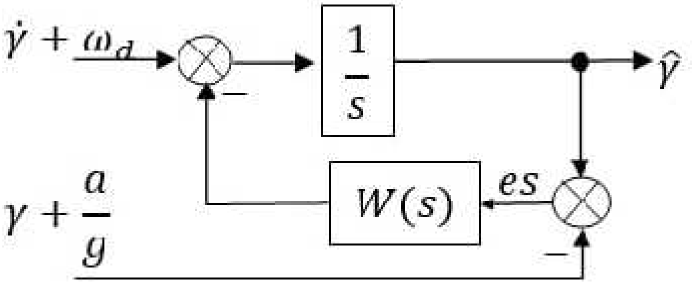


Figure 3.1 Block diagram of the CF according to the compensation scheme

The scheme shown in the figure allows you to separate the error signal and change it without changing the input signal. Thus, the integrator solves the problem of gyroscope zero drift, and the transfer function processes the ACC signal.

The equation of such a system can be written in the form:

$$\hat{\gamma} = \gamma + \frac{1}{s+W}\delta_1 + \frac{W}{s+W}\delta_2 = \gamma + \delta,$$

Where $\delta = \frac{1}{s+W}\delta_1 + \frac{W}{s+W}\delta_2$ is the error of system.

In Figure 3.1, the error signal "es" is not dependent on the input signal. In the presence of linear accelerations, the signal is determined by the accelerometer error. To reduce the influence of harmonic interference, it is reasonable to introduce a limiting unit before the filtering unit.

This link limits the incoming signal and ensures that the required oscillation values and transient time are obtained. However, it is necessary to choose the appropriate value of the transfer function to be limited. This is necessary because, if the limitations are large, the accelerometer interference signal will almost disappear, but then the gyroscope zero drift will appear, which holds back the ACC signal. If, on the other hand, the limitations have a small impact, the error of the accelerometer will be hardly to corrected.

3.1 Adding saturation and aperiodic unit in compensation scheme

Here is a compensation scheme with a limiting unit (saturation block in Simulink):

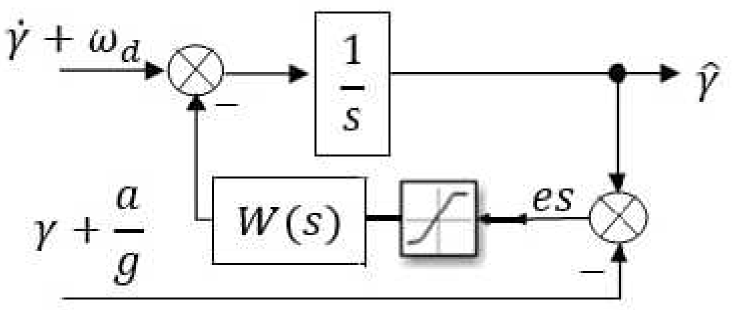
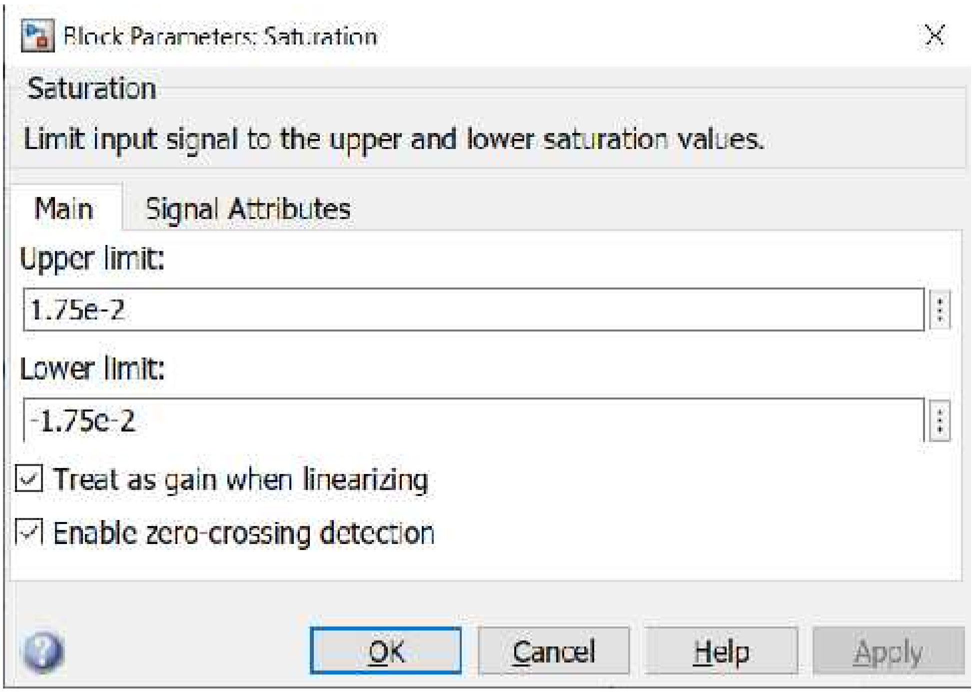


Figure 3.2 Block diagram of the CF according to the compensation scheme with a saturation unit block

Since the main purpose of the complementary filter is to eliminate the influence of gyroscope drift and reduce the influence of disturbances acting on the accelerometer, we will select the parameters of the limiting unit according to the requirements.

Saturation unit very helpful in our case because we can set any limit of values that this block can reject.

The Saturation block produces an output signal that is the value of the input signal bounded to the upper and lower saturation values. The upper and lower limits are specified by the parameters Upper limit and Lower limit.



Saturation

Limit input signal to the upper and lower saturation values.

Upper limit: 1.75e-2

Lower limit: -1.75e-2

☑ Treat as gain when linearizing

☑ Enable zero-crossing detection

Figure 3.3 Saturation block graphical user interface

When choosing the transfer function of the system, the basic rules of automatic control theory cannot be used, since the system is not linear. In this case, it is necessary to select such values of the transfer function to ensure the pulse damping. As disturbances, we will consider sinusoidal vibrations and impacts of repeated actions.

To evaluate the impact of accelerometer disturbances, we will develop a simulation model in Simulink and consider the effectiveness of introducing a signal limitation in the filter feedback.

To reproduce sinusoidal vibrations, we use the "Sine Wave" unit block. Let’s set the parameters necessary to ensure the following conditions:

- Frequency range from 20 to 120Hz;
- Amplitude 6g.

There are no built-in blocks in the Simulink environment to impacts of repeated actions. So, we will develop this case using the single pulse unit block, the signal delay block, and the signal repeater block. In this way, we create an imitation of the signal generated by continuous pulses of the required length and quantity.

Let’s set the values so that the following conditions are satisfied:

- amplitude 15 g;
- duration 10-15 ms;

- number of impacts 60;
- frequency 80 impacts per minute.

After simulating all the described actions in the Simulink environment, the link of the influence of dynamic errors will look like the following (Figure 3.3)

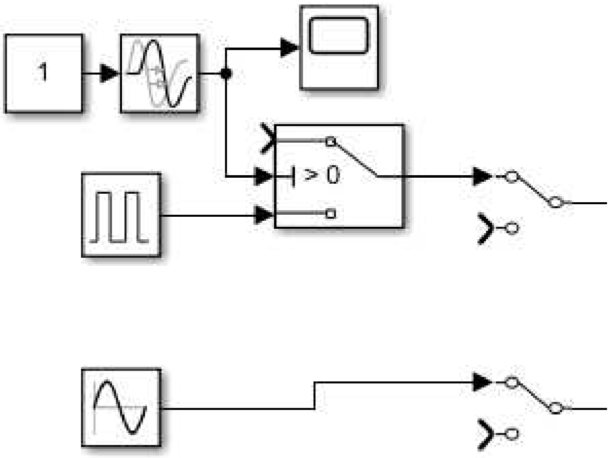


Figure 3.3 Model of a repetative pulses source in the Simulink environment

Let’s make sure that the necessary requirements for the repeating action unit are satisfied, since it was developed manually (Figure 3.4)

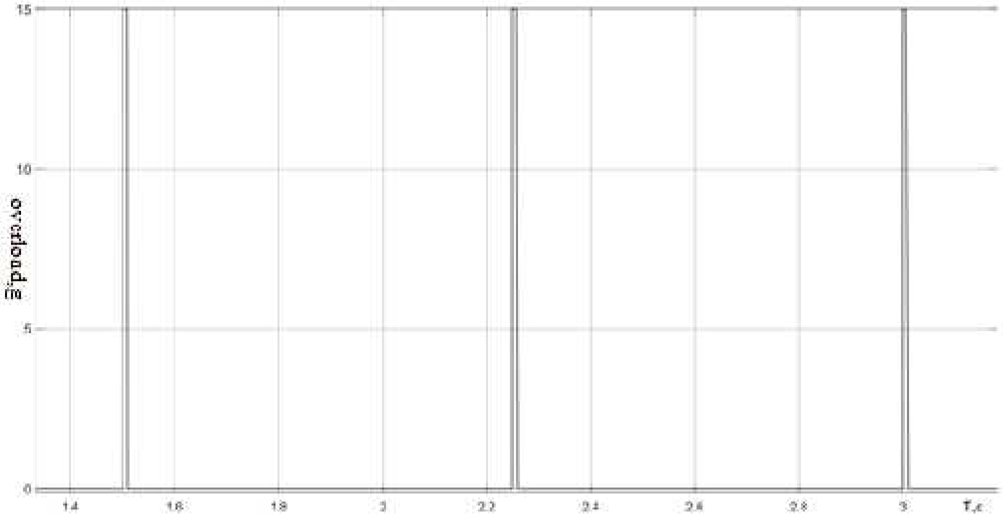


Figure 3.4 Display of a repeated action unit block

According to these graphs, we can see that the pulses are repeated in the same way, the required quantity of times. The overload amplitude reaches 15g, which is the required value. Thus, the specified parameters fully satisfy the required conditions.

As mentioned earlier, we will use a compensation scheme when building a CF model, as it allows us to work with the error signal itself. At the same time, it does not change the input signal. This makes it easier to work with acceleration impulses and evaluate the readings. The main transfer function will be the oscillating element, as described in the second section.

For simulation modelling and analysis of the data obtained, we will build a complementary filter using a compensation scheme in the Simulink environment.

First, let's consider a dynamic model without the use of a limiting unit. In this case, the first input of the constructed model is a gyroscope signal, and the second input is an accelerometer signal.

The accelerometer signal consists of two signal generators shown in Figure 3.3.

This model will simulate the harmonic signal generated by the gyroscope and the sinusoidal vibrations and impacts of repeated action generated by the accelerometer. Based on the calculations of the static model of the CF, the zero displacement offset of the gyroscope is accepted as 1e^{-4} °/sec.

The use of summers in the circuit allows us to isolate the error value, and the keys K1, K2, K3 provide easier signal analysis. Thus, by switching a particular key on or off, we can consider each action of the circuit separately.

Considering all of the above, let's develop the following circuit (Figure 3.5)

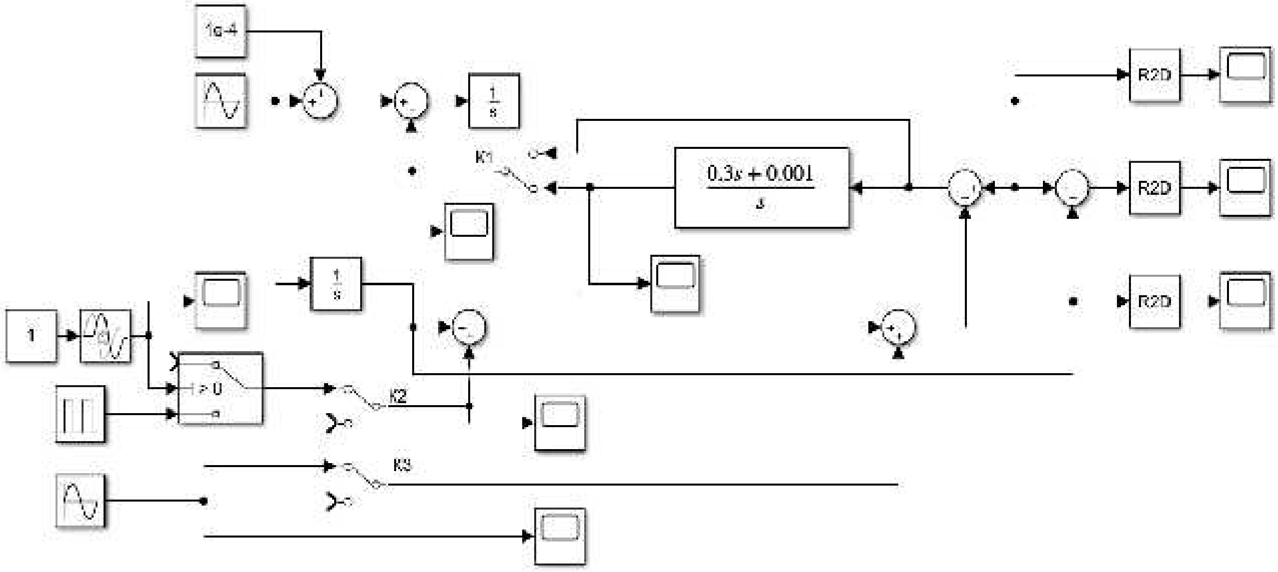


Figure 3.5 CF model by compensation scheme in Simulink environment

To estimate the error that we get with this model, we need to turn on all the keys and run the simulation. Then we will get the following graph (Figure 3.6)

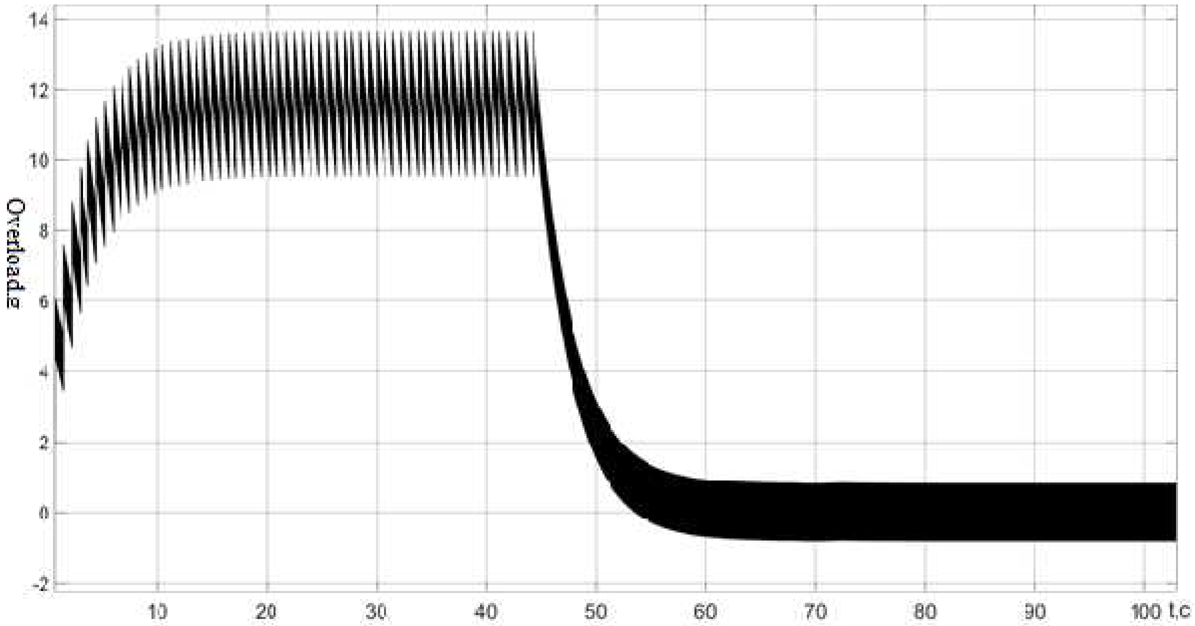


Figure 3.6 Dynamic model error, without interference

From the resulting graph, we can see that the signal is very noisy. It is necessary to reduce the amount of information that goes to the output to estimate the true error values. We can also see that the signal amplitude is very large and is almost 15g. To ensure the required 1% deviation, this value must be reduced as much as possible. Therefore, let’s try to add an aperiodic link before the main link to reduce this effect.

To achieve this, we create an additional, single, aperiodic link and place it on the scheme. We get the following diagram (Figure 3.7)

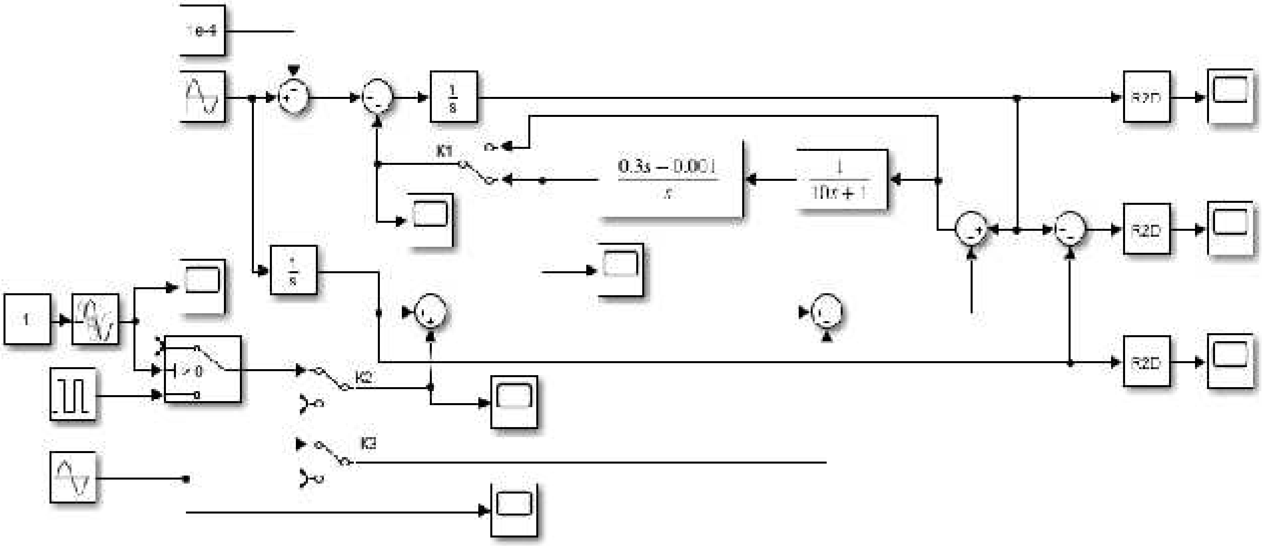


Figure 3.7 Model of the CF with the addition of an aperiodic link

Consider the result of the system with the addition of an aperiodic link:

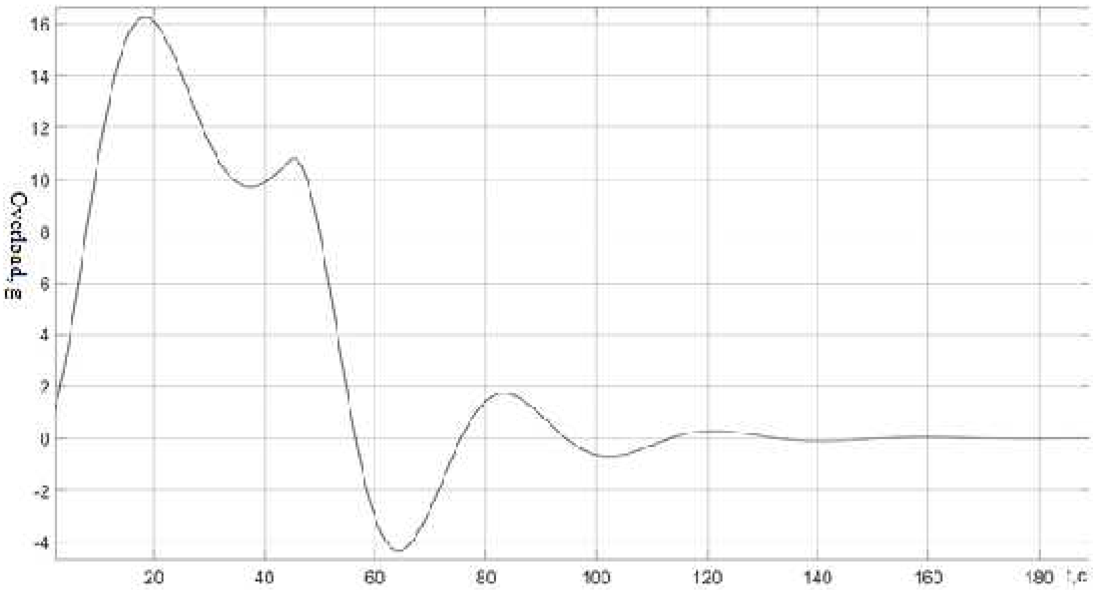


Figure 3.8 The CF error signal with the addition of an aperiodic link

Figure 3.8 shows that the addition of the aperiodic link has greatly reduced the signal vibration, making it clear and not noisy. The use of such transfer function coefficients made it possible to reduce vibrations by 100 times. However, the vibration amplitude increased to 16g.

3.2 Final version of the complementary filter scheme

To ensure the necessary conditions, we need to remove unnecessary oscillations and limit the growth of the error signal. To do this, we will use a saturation unit. Since the oscillation is created by the initial, oscillating link, the filter must be placed before it.

As previously mentioned, it is necessary to choose the right limitation so as not to completely extinguish the signal and not to leave it too large. Taking these conditions into account, we chose a signal limit in the range of ± $5e^{-4}$g.

Then the complementary filter model will look like this: (Figure 3.9)

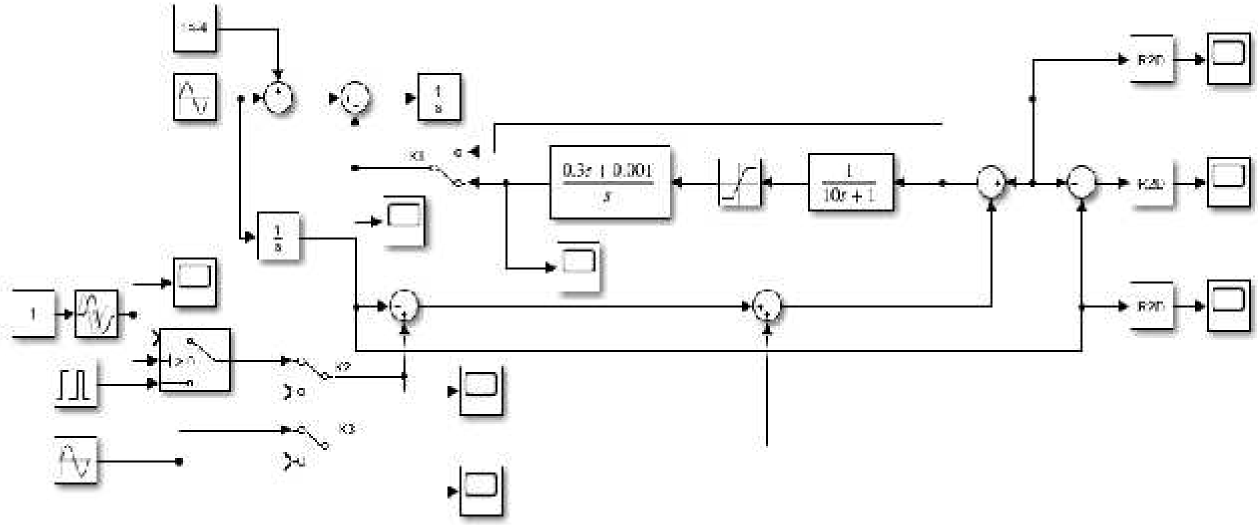


Figure 3.9 CF model with saturation and aperiodic units

The saturation unit should remove the signal peak and normalise the signal. Let's simulate the constructed model and get the following signal: (Figure 3.10)

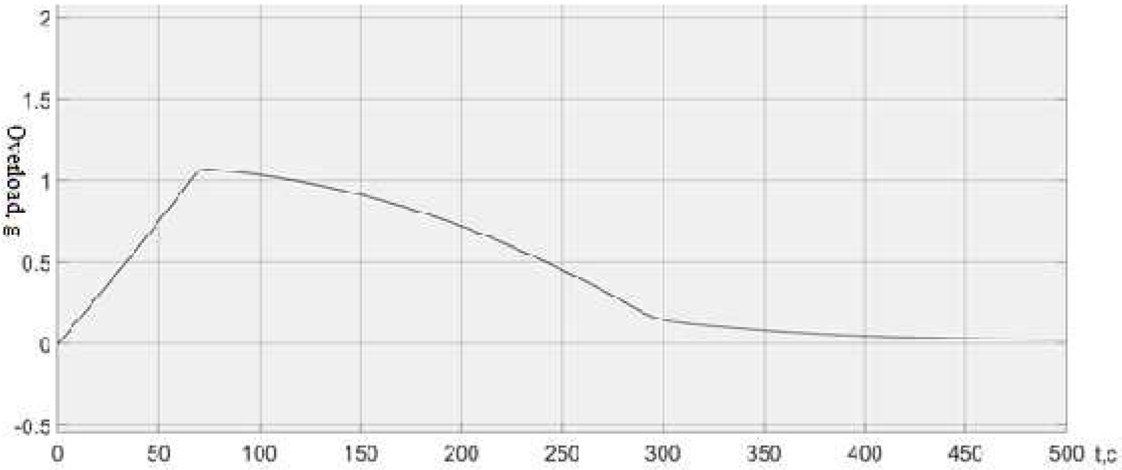


Figure 3.10 Error of whole model with saturation and aperiodic units

Figure 3.10 shows that the signal oscillations have been reduced. The amplitude of oscillations is slightly higher than 1g. That is, when using the saturation and aperiodic unit, the oscillations of the system were reduced by 15 times.

The results obtained from the developed model of a complementary filter for reducing dynamic and static errors fully satisfy the specified requirements.

3.3 Conclusion to chapter

The compensation scheme in the complementary filter was chosen as the most optimal, as it allows to separate the error signal and change it without changing the input signal.

We developed a source of repetitive pulses and a working simulation model to study the complementary filter for determining the UAV’s orientation

With the help of the Saturation unit block, the required data range was achieved
As a result, the work carried out ensures that all the tasks assigned are completed. The input parameters are fully consistent with the task. The absolute error is no more than 0.50, which is less than 1% of the total error. The error completely disappears over a period of time. The transient time is 400 seconds, which is not significant, since the resulting oscillations are very small.

Conclusion

In this paper, a scheme is developed to ensure the proper error when using a complementary filter consisting of an angular velocity sensor (gyroscope) and an accelerometer.

The use of a complementary filter is the most optimal in terms of "cost/quality" as gyroscopes and accelerometers are affordable sensors that do not require additional equipment like the GPS system. In combination, they provide a more accurate and reliable estimation of the UAV’s orientation.

It was found that the influence of dynamic errors in the development of a complementary filter is not sufficiently studied. Therefore, the main objective of this work was to reduce the influence of static and dynamic errors on the measurement result.

Two main schemes for constructing complementary filters are considered:

- Filtering scheme.
- Compensation scheme.

For filtering scheme we fully analysed that this scheme is not suitable for removing the effect of linear accelerations. Moreover, after studying the version of the construction with a first and second order filter, we found that the second one is not optimal and its use is not appropriate, since the difference from the first order is not significant

However, when studying dynamic errors, it is necessary to separate the signal of the error itself. For this purpose, the use of a compensation scheme is best applied. In this way, we change only the error signal, while the input signal remains unchanged.

To analyse the impact of errors, we considered the structure and parameters of the transfer function for our case

To study the influence of errors, we developed a model in Simulink that fully reproduces the operation of a complementary filter and allows us to analyse static and dynamic errors.

A structural diagram of the static and dynamic models of the complementary filter was developed.

The static and dynamic models of the complementary filter was developed in the Simulink environment.

Simulation modelling was performed and the results of calculations were presented. For our model we created some units manually, such as source of repetitive pulses and checked it operational efficiency.

According to the results of the work, all initial conditions were satisfied, and the error values were reduced by 100 times.

The total error of the static and dynamic system is 1-2 percent of the total system error. These results fully satisfy the project requirements.

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