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Кафедра авіаційних комп'ютерно-інтегрованих комплексів

ДОПУСТИТИ ДО ЗАХИСТУ
Завідувач випускової кафедри

______ Віктор СИНЄГЛАЗОВ

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Спеціальність 151 «Автоматизація та компю'терно-інтегровані технології»

Освітньо-професійна програма «Інформаційні технології та інженерія авіаційних комп'ютерних систем»

Тема: Паливомірна система літального апарату на основі датчиків тиску

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Київ – 2024

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

NATIONAL AVIATION UNIVERSITY

Faculty of Aeronautics,Electronics and Telecommunications

Department of aviation computer-integrated complexes

ADMIT TO DEFENSE
Head of the graduation department

_________ Viktor SINEGLAZOV

"______"________________2024

QUALIFICATION WORK

(EXPLANATORY NOTE)

GRADUATED EGREE OF EDUCATION

"BACHELOR"

Specialty 151 "Automation and computer-integrated technologies"

Educational and professional program " Information technology and engineering of aviation computer systems "

Topic: "Aircraft fuel measuring system based on pressure sensors "

Executor: student of group IK- 421Ba DUKA Yrii Serhiyovych

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Kyiv - 2024

НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ

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Освітній ступінь: бакалавр

Спеціальність 151 «Автоматизація та комп'ютерно-інтегровані технології»

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ЗАТВЕРДЖУЮ
Завідувач кафедри

__________ Віктор СИНЄГЛАЗОВ

“________”______________2024р.

ЗАВДАННЯ

на виконання кваліфікаційної роботи студента

Дуки Юрій Сергійовича

1. **Тема роботи :** “Паливомірна система літального апарату на основі датчиків тиску”.
2. **Термін виконання роботи :** з 29.04.2024р. до 03.06.2024р.
3. **Вихідні дані до роботи :** Розробка системи вимірювання рівня палива літального апарату на основі датчиків тиску. Дослідження існуючих систем вимірювання рівня палива . Дослідження алгоритму визначення залишку палива у певний момент часу.
4. **Зміст пояснювальної записки (перелік питань, що підлягають розробці) :**

   1.Аналіз паливної системи літального апарату. Опис функціонування паливної системи літка. Аналіз основних компонентів паливної системи. 2. Аналіз існуючих систем вимірювання рівня палива . 3. Дослідження гідростатичного датчика вимірювання тиску . 4. Принцип роботи системи вимірювання рівня палива на основі датчиків гідростатичного тиску. 5.

Розробка алгоритму визначення залишку палива . 6. Моделювання паливної системи літального апарату під час маневрування . Розробка системи вимірювання рівня палива у резервуарі.

5. **Перелік обов’язкового графічного матеріалу:** 1.Структурні схеми постачання палива .2.Структурна схема розміщення паливних баків на літальному апараті. 3. Структурна схема руху палива у резервуарі під час маневрування літального апарату . 4. Структурна схема паливного баку літального апарату. 5. Алгоритм визначення залишку палива під час маневрування . 6.Результати розробки руху паливної системи літального апарату під час маневрування та системи вимірювання рівня палива у резервуарі.

6. **Календарний план – графік**

Етапи виконання дипломного проекту (роботи)	Термін виконання роботи	Примітка
Аналіз паливної системи літака	05.05.2024	Виконано
Аналіз існуючих систем вимірювання палива	10.05.2024	Виконано
Аналіз системи вимірювання палива на основі датчика тиску	12.05.2024	Виконано
Аналіз проблеми вимірювання палива під час польоту літака	14.05.2024	Виконано
Аналіз методу вимірювання палива при горизонтальному русі літального апарату	17.05.2024	Виконано
Аналіз методу вимірювання палива при маневруванні літального апарату	20.05.2024	Виконано
Моделювання процесів	22.05.2024	Виконано
Аналіз результатів дослідження	25.05.2024	Виконано

7. **Дата видачі завдання** 29.04.2024

Керівник : ____ СМІРНОВ.О.І

(підпис)

Завдання прийняв до виконання ________________________ ДУКА.Ю.С

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NATIONAL AVIATION UNIVERSITY

Faculty of Aeronautics,Electronics and Telecommunications

Department of aviation computer-integrated complexes

Educational degree : Bachelor

Specialty 151 "Automation and computer-integrated technologies"

Educational and professional program " Information technology and engineering of aviation computer systems "

APPROVED
Head of the graduation department

_________ Viktor SINEGLAZOV

"______"________________2024

TASK

For the student's qualification work

DUKA YRII SERHIYOVYCH

1. **The thesis title :** "Aircraft fuel measuring system based on pressure sensors"
2. **The term of the project :** from 29.04.2024p until 03.06.2024
3. **Output data to the project :** Development of an aircraft fuel level measurement system based on pressure sensors. Study of existing fuel level measurement systems. Study of the algorithm for determining the remaining fuel at a certain point in time.
4. **Contents of the explanatory note :** 1. Analysis of the aircraft fuel system. Description of the functioning of the fuel system of the aircraft. Analysis of the main components of the fuel system. 2. Analysis of existing fuel level measurement systems. 3. Study of the hydrostatic sensor for pressure measurement. 4. The principle of operation of the fuel level measurement system based on hydrostatic pressure sensors. 5. Development of an algorithm for determining the remaining fuel. 6. Modeling of the fuel system of the aircraft

during maneuvering. Development of a fuel level measurement system in the tank.

5. **List of required illustrative material :** 1. Structural diagrams of fuel supply. 2. Structural diagram of placement of fuel tanks on the aircraft. 3. Structural diagram of the movement of fuel in the tank during maneuvering of the aircraft. 4. Structural diagram of an aircraft fuel tank. 5. The algorithm for determining the remaining fuel during maneuvering 6. The results of the development of the movement of the fuel system of the aircraft during maneuvering and the system for measuring the level of fuel in the tank.
6. **Planned schedule :**

Task	Execution term	Execution mark
Analysis of the aircraft fuel system	05.05.2024	Completed
Analysis of the existing fuel measurement systems	10.05.2024	Completed
Analysis of the fuel measurement system based on the pressure sensor	12.05.2024	Completed
Analysis of the problem of fuel measurement during the flight of the aircraft	14.05.204	Completed
Analysis of the fuel measurement method during the horizontal movement of the aircraft	17.05.2024	Completed
Analysis of the fuel measurement method during aircraft maneuvering	20.05.2024	Completed
Process modeling	22.05.2024	Completed
Analysis of research results	24.05.2024	Completed

7. **Issue data of the task :** 29.04.2024

Supervisor : ____ SMIRNOV.O.I

The task was accepted by : _______________________________ DUKA.Y.S

РЕФЕРАТ

Пояснювальна записка кваліфікаційної роботи “Паливомірна система літального апарату на основі датчиків тиску ”.

ПАЛИВОМІРНА СИСТЕМА ЛІТАЛЬНОГО АПАРАТУ, ДОСЛІДЖЕННЯ МЕТОДІВ ЗНАХОДЖЕННЯ ЗАЛИШКУ ПАЛЬНОГО ЛІТАЛЬНОГО АПАРАТУ, ГІДРОСТАТИЧНИЙ ДАТЧИК ТИСКУ , ПАЛИВОМІРНА СИСТЕМА ОЦІНКИ ЗАЛИШКУ ПАЛЬНОГО НА БАЗІ ДАТЧИКА ТИСКУ, МАНЕВРУВАННЯ ЛІТАЛЬНОГО АПАРАТУ.

Предмет дослідження : Паливомірна система літального апарату.

Мета кваліфікаційної роботи : Розробка та імплементація паливомірної системи, яка використовує гідростатичний датчик тиску в баку літака для більш точного визначення залишку пального.

Метод дослідження : Аналіз літературних джерел , порівняння наявних методів знаходження залишку пального, практичне впровадження технічних рішень, експериментальні вимірювання.

Об’єкт дослідження : Паливомірна система літального апарату на основі датчиків тиску

Основні результати дослідження : Використання гідростатичного датчика в паливомірній системі при маневруванні літального апарату дозволило досягти більш точних та надійних вимірювань на відміну від інших методів оцінки залишку палива. Розроблена система дозволяє ефективно враховувати вплив різних факторів, таких як тиск, температура , висота польоту , зміну положення літального апарату під час руху на визначення залишку пального.

Рекомендації та подальші напрями досліджень : Результати роботи можуть бути використані в практичній діяльності авіаційних підприємств для оптимізації паливомірної системи та підвищення безпеки польотів. Подальші дослідження можуть бути спрямовані на вдосконалення технічних рішень та розширення можливостей системи в різних умовах експлуатації літаків.

ABSTRACT

Explanatory note of the qualification work: “Aircraft fuel measuring system based on pressure sensors”.

AIRCRAFT FUEL SYSTEM, STUDY OF METHODS FOR DETERMINING AIRCRAFT FUEL REMAINDER, HYDROSTATIC PRESSURE SENSOR, FUEL MEASUREMENT SYSTEM FOR EVALUATION OF FUEL REMAINDER BASED ON PRESSURE SENSOR, AIRCRAFT MANEUVERING.

The subject of the study: Aircraft fuel measuring system.

The purpose of the qualification work : Development and implementation of a fuel measuring system that uses a hydrostatic pressure sensor in the aircraft tank to more accurately determine the remaining fuel.

Research method : Analysis of literary sources, comparison of available methods of finding fuel residue, practical implementation of technical solutions, experimental measurements.

The object of the study : Aircraft fuel measuring system based on pressure sensor.

The main results of the study: The use of a hydrostatic sensor in the fuel measuring system during maneuvering of the aircraft made it possible to achieve more accurate and reliable measurements in contrast to other methods of estimating the remaining fuel. The developed system allows you to effectively take into account the influence of various factors, such as pressure, temperature, flight altitude, changes in the position of the aircraft during movement on the determination of the remaining fuel.

Recommendations and further directions of research : The results of the work can be used in the practical activities of airlines to optimize the fuel measuring system and improve flight safety. Further research can be aimed at improving technical solutions and expanding the capabilities of the system in different operating conditions of the aircraft.

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LIST OF ABBREVIATIONS

AFS – Aircraft fuel system

FS – Fuel system

FMS – Fuel measurement system

FMSs – Fuel measuring systems

APU – Auxiliary power unit

MLW – Maximum landing weight

AFM – Active fuel management

POH – Pilot’s operating handbook

HS – Hydrostatic sensor

CAN – Controller area network

GPS – Global positioning system

IoT – Internet of things

FSL – Full-scale range

HVAC – Heating, ventilation, and air conditioning

CG – Center of gravity

EA – Euler angles

HPS – Hydrostatic pressure sensor

T – Tetrahedron

FM – Fuel mirror

FLS – Fuel level sensor

FLSs – Fuel level sensors

INTRODUCTION

Improving the safety of aircrafts flights has always been one of the important tasks of aircraft designers, maintenance and flight personnel of aviation, because it is a complex task that can be solved only by the efforts of all specialists related to aviation technology. A big role in solving this task belongs to the on-board equipment, its accuracy, reliability and technical condition. Among this equipment, the role of fuel measurement systems (FMS) is especially highlighted.

Fuel is one of the main items of transport costs, besides, fuel is often the main object of various frauds. Such circumstances make the use of fuel consumption control systems the most relevant, as they are able to protect you from difficulties associated with excessive fuel consumption.

That is why, with the development of airplanes, fuel gauges are also being improved, which over time have evolved from a simple "water gauge" glass to a complex hydrostatic device.

Over time, capacitive fuel gauges were created, the readings of which almost did not depend on the instability of the dielectric permeability of the fuel, but their readings largely depended on the insulation resistance of the sensors and the connecting line. Due to the instability of this parameter, the error of the fuel gauges sometimes exceeded 10-15%, which complicated their operation and caused crews to distrust the readings of these devices.

The search for ways to increase the accuracy of fuel gauges is conducted in various directions: the search for new measurement methods is underway, the design and properties of capacitive fuel gauges are being improved. As a result of the search, it was found that hydrostatic fuel gauges are the most promising. Especially when maneuvering the aircraft in flight.

The diploma work will consist of sections covering various aspects of the development and implementation of the residual fuel estimation system during aircraft maneuvering in flight. Analysis of literary sources, comparative analysis of existing systems, description of mathematical models and hardware, consideration of practical problems and advantages of the system - these are only some aspects that will be reflected in the work. The results of the research will be created outside the boundaries of modern aviation technology and economics.

CHAPTER 1

RESEARCH OF THE FS OF THE AIRCRAFT

1.1. Role fuel system in aircraft

An aircraft's fuel system (AFS) allows fuel to be loaded, stored, managed and delivered to the aircraft's power plant (engine(s)).

Fuel systems vary greatly from aircraft to aircraft due to the relative size and complexity of the aircraft on which they are installed. In its simplest form, the fuel system would consist of a single gravity-fed fuel tank with a corresponding fuel line connecting it to the aircraft engine. In a modern multi-engine passenger or cargo aircraft, the fuel system is likely to consist of several fuel tanks, which may be located in the wing or fuselage (or both). Each tank will potentially be equipped with internal fuel pumps and have appropriate valves and piping to feed the engines, fill and drain fuel, isolate individual tanks and, in some cases, dump fuel or optimize the aircraft's center of gravity.

While aircraft fuel systems are not generally regarded as the most glamorous feature of aircraft functionality they are an essential feature of all aircraft. Their implementation and functional characteristics play a critical role in the design, certification and operational aspects of both military and commercial (civil) aircraft. In fact the impact of fuel system design on aircraft operational capability encompasses a range of technologies that are much more significant than the non specialist would at first realize, particularly when considering the complexities of large transport and high speed military aircraft applications.

The fuel system is designed to provide an uninterrupted flow of clean fuel from the fuel tanks to the engine. The fuel must be available to the engine under all conditions of engine power, altitude, attitude, and during all approved flight maneuvers. Two common classifications apply to fuel systems in small aircraft: gravity-feed and fuel-pump systems.

Enhancements to the fuel system commonly found on aircraft include:

- Single point refueling/defueling - the refuelling hose is connected to a single point on the aircraft, usually located underwing or somewhere on the fuselage and all tanks are fuelled or defuelled by means of a manifold connecting to all tanks.
- Fuel pump redundancy - multiple fuel pumps in each tank to ensure fuel is accessible in the event of a single pump failure.
- Provision of fuel tanks in the outer portion of the wings to reduce wing bending. The fuel in these tanks is generally not burned until late in the flight.
- Provision in the fuel system to supply an Auxiliary Power Unit (APU);
- Automated inflight transfer of fuel from the wing tanks to trim tanks in the horizontal stabiliser. Moving the fuel to the trim tank optimizes the centre of gravity and reduces the fuel burn.
- Fuel dumping provisions. In the event of an unexpectedly early landing, excess fuel can be dumped to reduce the aircraft landing weight to or towards the permitted MLW (Maximum landing weight).
- Robust fuel management, indicating and warning systems - depending upon the aircraft, these can include:
    - Fuel quantity by tank.
    - Total fuel quantity remaining.
    - Fuel used.
    - Estimated fuel remaining at intended destination.
    - Fuel temperature by tank.
    - Automatic selection of most appropriate fuel tank dependent upon phase of flight automatic fuel transfer.
    - Warnings and cautions for items such as :
        - Low fuel quantity.
        - Low fuel pressure.

- Low fuel temperature

1.2. Threat's aircraft fuel system

There are several threats associated with the misuse or malfunction of an aircraft's fuel system. They include:

- Fuel Leak - Fuel can leak at the engine, from the tank or anywhere in between due to fuel tank or fuel line rupture.
- Fuel Imbalance - Fuel imbalance can occur as a result of improper refueling techniques, poor fuel management, engine failure or fuel leak.
- Mechanical failure of a fuel pump.
- Fuel Freezing - In gas turbine powered jet aircraft flown at high altitude for long periods, fuel temperature can be a critical factor. Minimum allowable fuel temperatures are less likely to be a factor on the operation of turboprop aircraft.
- Electrical failure - may limit the availability of fuel pumps and fuel system indications.

Effects :

- A fuel leak from an engine can often be resolved by shutting down the affected engine. A tank leak due to a rupture in the tank will result in the loss of some or all of the fuel in that tank. If a fuel line is ruptured, it could result in some fuel being un useable.
- An uncorrected fuel imbalance can lead to difficulty in controlling the aircraft.
- A pump failure could result in the inability to use the fuel in the affected tank. This may be mitigated by a second (or even a third) pump in the same tank.
- Fuel freezing can lead to loss of power due to fuel starvation and potentially can result in engine failure.
- In the event of electrical failure, some, or potentially all, fuel tank boost pumps will be lost. In most aircraft, gravity fuel feeding is only possible from some of the fuel tanks. Descent may be required to comply with the maximum allowable fuel gravity feed altitude. Diversion may be required due to unusable fuel.

1.3. Getting fuel into the engine

The gravity-feed system utilizes the force of gravity to transfer the fuel from the tanks to the engine. For example, on high-wing airplanes, the fuel tanks are installed in the wings. This places the fuel tanks above the carburetor, and the fuel is gravity fed through the system and into the carburetor. If the design of the aircraft is such that gravity cannot be used to transfer fuel, fuel pumps are installed.

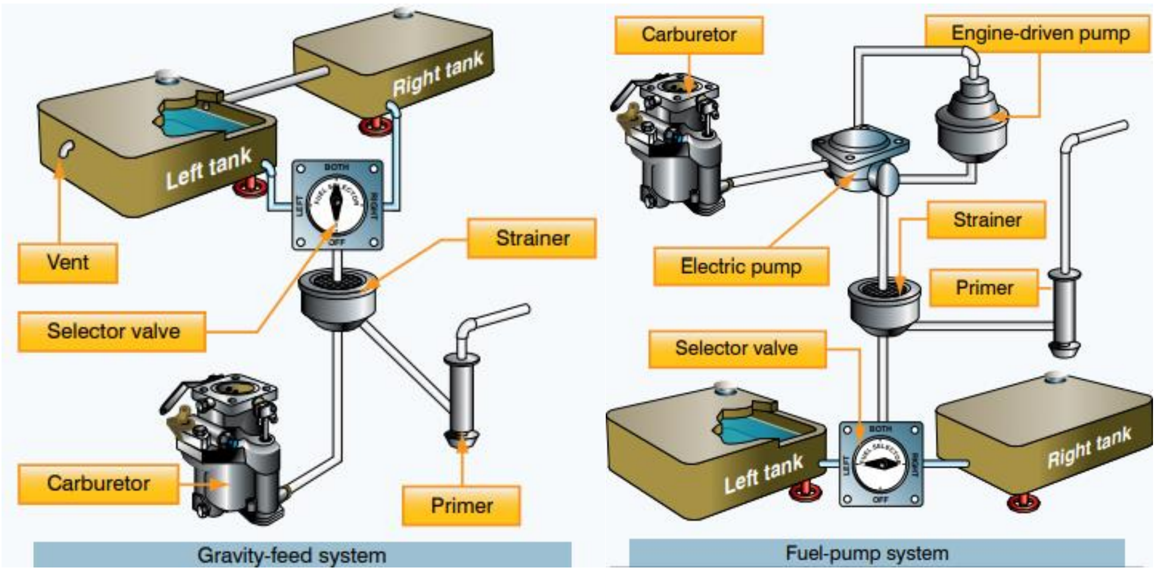

Fig.1.1.Gravity-feed and fuel-pump system

Aircraft with fuel-pump systems have two fuel pumps. The main pump system is engine driven with an electricallydriven auxiliary pump provided for use in engine starting and in the event the engine pump fails. The auxiliary pump, also known as a boost pump, provides added reliability to the fuel system. The electrically-driven auxiliary pump is controlled by a switch in the flight deck.

1.4. Main components of the aircraft fuel system

1.4.1.Fuel tank

Fuel tanks vary in location, size and shape depending on the needs of the aircraft. What remains constant in every fuel system is that the fuel tank (or tanks) must be perfectly positioned to store and deliver clean fuel to the engine at the correct pressure and flow rate regardless of operating conditions.

Many small single-engine aircraft have fuel tanks located above the wing and use a gravity feed system to deliver fuel to the engine. Other tanks are located under the wing and use pumps or a fuel injection system to supply fuel. They can be separate components or integrated into the wing structure.

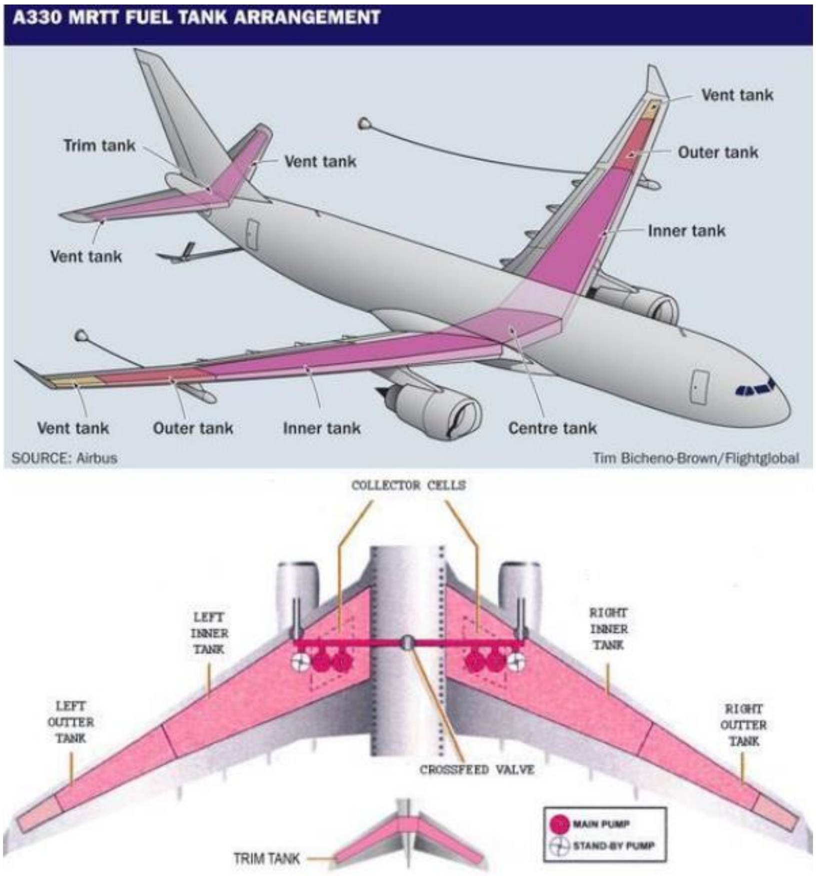

Fig.1.2. Location of fuel tanks on an Airbus 330

1.4.2. Fuel gauges

The fuel quantity gauges indicate the amount of fuel measured by a sensing unit in each fuel tank and is displayed in gallons or pounds. Aircraft certification rules require accuracy in fuel gauges only when they read “empty.” Any reading other than “empty” should be verified. Do not depend solely on the accuracy of the fuel quantity gauges. Always visually check the fuel level in each tank during the preflight inspection, and then compare it with the corresponding fuel quantity indication.

1.4.3. Fuel selectors

The fuel selector valve allows selection of fuel from various tanks. A common type of selector valve contains four positions: LEFT, RIGHT, BOTH, and OFF. Selecting the LEFT or RIGHT position allows fuel to feed only from the respective tank, while selecting the BOTH position feeds fuel from both tanks. The LEFT or RIGHT position may be used to balance the amount of fuel remaining in each wing tank.

1.4.4. Carburetor

The carburetor is part of the engine's induction system and is responsible for combining and mixing air and fuel.

1.4.5. Fuel strainers , sumps and drains

After leaving the fuel tank and before it enters the carburetor, the fuel passes through a strainer that removes any moisture and other sediments in the system. Since these contaminants are heavier than aviation fuel, they settle in a sump at the bottom of the strainer assembly. A sump is a low point in a fuel system and/or fuel tank. The fuel system may contain a sump, a fuel strainer, and fuel tank drains, which may be collocated.

The fuel strainer should be drained before each flight. Fuel samples should be drained and checked visually for water and contaminants.

Water in the sump is hazardous because in cold weather the water can freeze and block fuel lines. In warm weather, it can flow into the carburetor and stop the engine. If water is present in the sump, more water in the fuel tanks is probable, and they should be drained until there is no evidence of water. Never take off until all water and contaminants have been removed from the engine fuel system. Because of the variation in fuel systems, become thoroughly familiar with the systems that apply to the aircraft being flown. Consult the AFM/POH for specific operating procedures.

1.5. Fuel contamination

Accidents attributed to powerplant failure from fuel contamination have often been traced to:

- Inadequate preflight inspection by the pilot.
- Servicing aircraft with improperly filtered fuel from small tanks or drums.
- Storing aircraft with partially filled fuel tanks.
- Lack of proper maintenance.

Fuel should be drained from the fuel strainer quick drain and from each fuel tank sump into a transparent container and then checked for dirt and water. When the fuel strainer is being drained, water in the tank may not appear until all the fuel has been drained from the lines leading to the tank. This indicates that water remains in the tank and is not forcing the fuel out of the fuel lines leading to the fuel strainer. Therefore, drain enough fuel from the fuel strainer to be certain that fuel is being drained from the tank. The amount depends on the length of fuel line from the tank to the drain. If water or other contaminants are found in the first sample, drain further samples until no trace appears.

Water may also remain in the fuel tanks after the drainagefrom the fuel strainer has ceased to show any trace of water. This residual water can be removed only by draining the fuel tank sump drains.

Water is the principal fuel contaminant. Suspended water droplets in the fuel can be identified by a cloudy appearance of the fuel, or by the clear separation of water from the colored fuel, which occurs after the water has settled to the bottom of the tank. As a safety measure, the fuel sumps should be drained before every flight during the preflight inspection.

Fuel tanks should be filled after each flight or after the last flight of the day to prevent moisture condensation within the tank. To prevent fuel contamination, avoid refueling from cans and drums.

CHAPTER 2

INTRODUCTION TO AIRCRAFT FUEL MEASURING SYSTEMS

2.1. What is level measurement ?

Level measurement is the measurement of liquid level. In the process, measuring the level is very important, and thanks to this we can ensure that the process is carried out in a controlled manner and safely.

2.2. Role fuel measuring system in aircraft ?

There are many different signs by which fuel gauges are classified, but the classification according to the level measurement method is considered the main one. Different methods satisfy the requirements for metrological and operational characteristics in different ways. Therefore, we will consider the main ones in order to identify the best and most promising ones among them for further improvement.

The fuel measuring system (FMS) is designed to measure the fuel content and reserve in each tank on the aircraft during refueling and in flight, as well as to automatically control fueling and fuel consumption.

Fuel metering and management systems are frequently custom-designed to match the requirements of each aircraft type. The system's designers adhere to requirements for maturity at entry-into-service, the most up-to-date technologies, safety, dependability, correctness, and maintainability while reducing the customer's total cost of ownership.

The mass of fuel on board the aircraft is more than half of its take-off mass. Therefore, the exact determination of its quantity and costs is one of the most important tasks, the solution of which allows to ensure the operation of the aircraft's power plants. Based on the accurate determination of the fuel reserve and consumption, it is possible to calculate the range and duration of the flight, solve the problems of automatic control of the order of fuel production from the tanks, automatically pump fuel from tank to tank to maintain the correct centering of the aircraft, generate an alarm about the critical remaining fuel, determine the order of refueling the tanks fuel, etc.

2.3. The main functions of the fuel measuring system

The system (FMS) must perform the following functions:

- Measurement of fuel volume and level during refueling and in flight.
- Control of the sequence of filling the fuel system of the aircraft with fuel, the sequence of fuel use according to the given program.
- Calculation based on fuel supply information of the actual position of the center of gravity and control of the position of the center of gravity of the aircraft.
- Signaling about the maximum permissible fuel level and the fuel level corresponding to the aeronautical reserve, about the operability of the fuel measuring system.
- Issuance of a system failure signal in the emergency registration system and on the emergency alarm system panel.

2.4. Problems of measuring the level of fuel in an airplane

The most important aspects of flight planning from a safety point of view are the calculation of the fuel requirements for the trips and the fuel reserves of the aircraft. Calculation of fuel in airplanes is complicated for the following reasons :

- Fuel consumption varies depending on the speed of the aircraft, the altitude of the aircraft, and the ambient temperature. The factors listed above cannot be predicted in advance.
- Fuel consumption depends on the weight of the aircraft.

In jet aircraft, fuel is measured in pounds due to the fuel volume is changed based on the temperature. This is very critical when a jet flies in high altitudes where the temperature will be -40 to -50 Fahrenheit. Furthermore, fuel is consumed by mass rather than volume.

2.5. Fuel level sensors in airplanes

Level sensors are instruments used to detect or measure the level of liquid or powder in tanks or containers.

We can use the same leveling mechanism as in cars to calculate smaller planes, but we can't use it in larger planes. To determine the fuel level in large aircraft, we must use multiple sensors due to the large size of the aircraft. Some level sensors have a very small margin of error, so we cannot use this type of sensor. We need very precise sensors because even a small error can have very catastrophic consequences.

In airplanes, fuel is stored in rectangular wings with a very detailed internal structure. A common fuel measurement system consists of a series of fuel gauges installed in the tanks to directly measure the fuel level inside the tanks, which is proportional to the amount of fuel.

2.6. What should be the fuel level sensors

For the general determination of the liquid level in a specific tank, there is a wide range of available measurement technologies, including mechanical, magnetic, pressure (hydrostatic, bubble, differential), electrostatic (capacitive, inductive), radar. and ultrasonic sensors.

Aircraft fuel gauges are used to measure the amount of fuel in the aircraft's fuel tanks. This information is critical to flight safety as it allows pilots to know how much fuel is available and make necessary adjustments to the flight plan.

Aircraft fuel level sensors must be able to withstand the harsh conditions found in aircraft, such as extreme temperatures, vibration, and turbulence. Sensors in aircraft must be able to cope with altitude changes.They must also be accurate and reliable, as even a small error in fuel level measurement can have serious consequences.

2.7. Challenges of aircraft fuel level sensor design

Here are some of the challenges of aircraft fuel level sensor design:

- Accuracy: the fuel level sensors must be accurate enough to provide pilots with accurate information about the amount of fuel available.
- Reliability: the fuel level sensors must be reliable enough to provide accurate information throughout the life of the aircraft.
- Environmental resistance: the fuel level sensors must be able to withstand the harsh environmental conditions that they are exposed to.
- Cost: the fuel level sensors must be cost-effective to manufacture and install.

- Dynamic Response: tuel level in an aircraft's fuel tank can change rapidly, especially during flight. This means that the fuel level sensors must be able to respond quickly to changes in the fuel level.
- Contaminated Fuel: fuel in an aircraft's fuel tank can be contaminated with water or other foreign materials. This can cause the fuel level sensors to read incorrectly.

2.8. Factors that affect the accuracy of aircraft fuel level sensors

Here are some of the factors that can affect the accuracy of aircraft fuel level sensors:

- Fuel sloshing: fuel sloshing can cause errors in fuel level measurement, as the float or capacitance sensor may not be able to accurately measure the height of the fuel.
- Fuel temperature: fuel temperature can also cause errors in fuel level measurement, as the fuel expands when it is heated, and contracts when it is cooled. This means that the fuel level will be different at different temperatures.
- Fuel contamination: fuel contamination can also cause errors in fuel level measurement, as contaminants can settle on the fuel level sensors and cause them to read incorrectly.

2.9. Advantages and disadvantages of fuel level sensors in aircrafts

Advantages :

- Providing information : they provide real-time information about the amount of fuel on board.
- Cost : they are relatively inexpensive to install and maintain.
- Improved flight safety : by knowing the amount of fuel on board, pilots can make informed decisions about the flight plan and ensure that there is enough fuel to complete the flight safely.
- Reduced fuel costs: by monitoring the fuel level, pilots can avoid wasting fuel by flying with too much fuel or by running out of fuel before reaching the destination.

- Increased aircraft efficiency: by knowing the amount of fuel on board, pilots can optimize the aircraft's performance and improve its fuel efficiency.

Disadvantages :

- Fuel sloshing : they can be affected by fuel sloshing.
- Fuel temperature : they can be affected by fuel temperature.
- Fuel contamination : they can be affected by fuel contamination.

CHAPTER 3
THEFT OF FUEL

3.1. Understanding the impact of fuel theft

Fuel theft can have a significant impact on businesses, especially those that rely on a fleet of vehicles for their operations. This can present several challenges for businesses, including financial losses that can impact the company's overall profitability.

Additionally, it can lead to operational disruptions, causing unexpected delays in deliveries and vehicle downtime. This activity can result in damage to the vehicles themselves, adding more to fleet maintenance costs, with potential issues such as punctured fuel tanks or other forms of tampering.

Overall, fuel theft poses significant safety risks, especially if it involves meddling with vital components of the vehicle, potentially jeopardising the safety of drivers and other motorists if the driver is unaware of the potential vehicle damage through fuel theft and continues to operate their vehicle.

3.2. Signs of fuel theft

Thieves throughout South Africa have been actively seeking inventive methods to steal fuel from vehicles and filling stations alike. Surprisingly, most fuel theft incidents don't occur by criminals. We're not saying criminals don't play a part but the majority of fuel theft frequently happens from the inside. Yes, you guessed it — your employees.

This is referred to as skimming, it involves employees syphoning a small amount of fuel from a vehicle's tank for their personal use, thus saving money on their fuel expenses. Coincidentally, 'skimming' or 'shimming' can also mean a form of fuel card fraud.

The signs of fuel theft can include:

- Sudden drops in fuel levels without reasonable explanation.
- Gaps between fuel purchase records and actual usage.
- Unexplained high fuel expenses.

- Evidence of tampering with fuel tanks or petrol cap locks.
- Unexplained variations in vehicle routes.
- Unauthorised vehicle activity during off-hours.

3.3. Protection against fuel theft and excessive fuel usage

Guarding against fuel theft and unnecessary fuel expenses is a key component in maintaining a successful operation. Implementing proactive measures can ensure the security of your fuel and the optimisation of your fuel resources.

Valuable tips to assist you in minimizing fuel theft and wastage:

- Improve your tracking system : invest in an advanced tracking system to closely monitor your fuel consumption and track vehicle movements in real time. It will help you instantly identify any fuel usage irregularities, solve causing issues and save money.
- Secure level tanks : employ robust locking mechanisms on your fuel tanks to deter potential thieves. Anti-siphoning devices can further fortify your defences against unauthorised fuel access.
- Regular audits : conduct frequent audits to oversee fuel usage meticulously. Identifying any inconsistencies early on can help address potential fuel theft issues before they escalate.
- Educate your pilots : educate your pilots on fuel-efficient driving practices, including maintaining consistent speeds, minimising idling time, and planning optimal routes to reduce fuel consumption.
- Utilise fuel monitoring software : implement user-friendly fuel monitoring software integrated into your fleet management system. This technology enables you to monitor fuel levels and promptly detect any suspicious activities.
- Install surveillance systems : consider installing visible surveillance cameras at fueling stations and parking areas. Not only do they act as a deterrent to potential theft, but they also serve as concrete evidence in case of any attempted fuel-related crimes.

- Establish clear guidelines : develop and enforce transparent fuel usage policies within your organisation. Clearly define procedures for fuel card usage, refuelling protocols, and reporting any unusual activities, fostering a culture of accountability and responsibility.

3.4. Fuel level sensor as a theft prevention method

The high cost and shortage of fuel today encourage more economical use of fuel. Recently, more and more companies are implementing fuel consumption control systems in their enterprises in order to minimize fuel theft and misuse of vehicles.

Control of fuel consumption can be carried out in several ways. The choice depends on the type of vehicles and the budget that the company is ready to allocate for the implementation of the fuel control system:

- Use of fuel level sensors.
- Use of fuel consumption meters.
- Receiving data from the CAN bus.

The best option is a combination of several methods, for example, installing fuel level sensors and reading data from the on-board computer.

Airlines usually use fuel level sensors in combination with modern GPS trackers. Fuel level sensors are installed directly in the fuel tank and allow monitoring:

- Track location in real time.
- Control fuel consumption.
- Control mileage.
- Get a reading of the fuel level in liters.
- Control gas stations.
- Track fuel drain.
- Receive notifications about refueling and drain.

Let's take a closer look at fuel control using fuel level sensors. This is probably the main means of fuel control used in businesses where thefts and spills have been recorded.

Due to the linear measurement of the fuel level in the tank, the theft of even a few liters will be reflected in the monitoring system.

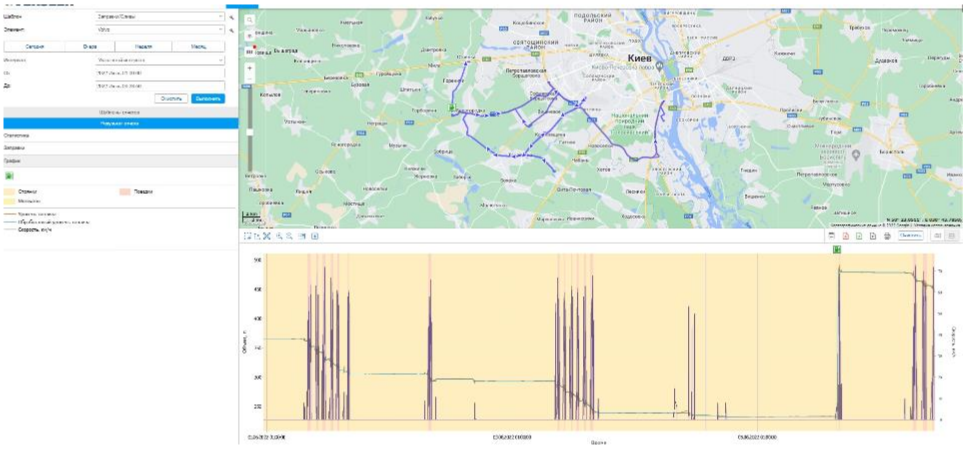

Fig.3.1.System monitoring

Depending on the height of the fuel tank, sensors with different measuring probe lengths are used. The sensor is installed without interfering with the aircraft's fuel system. Due to the fact that the fixation of the fuel level is linear and smooth, it is possible to determine the fuel drain quite accurately and in a timely manner.

3.5. Benefits of saving petrol

Every drop of stolen fuel is a loss that adds up over time. Fuel theft can result in increased vehicle repair costs, which are usually much more expensive than the stolen fuel itself.

By recognising the various benefits associated with preventing fuel theft, managers can elevate the overall performance and safety of their operations.

Here’s what you can gain from solving your fuel theft problem:

- Cost savings : efficient fuel management helps reduce fuel wastage and prevents unauthorised fuel usage, resulting in significant cost savings over time.
- Enhanced operational efficiency : By closely monitoring fuel usage, you can optimise routes, reduce idle time, and improve overall fleet efficiency, leading to better productivity and timely deliveries.

- Maintenance optimization : effective fuel management can contribute to the proper maintenance of vehicles, ensuring that they operate at their optimal level and reducing the likelihood of unexpected breakdowns.
- Improved accountability: implementing measures to prevent fuel theft fosters a culture of accountability among drivers and employees, promoting responsible behaviour and discouraging fraudulent activities.
- Regulatory compliance: by maintaining accurate fuel records and preventing fuel-related irregularities, you can ensure compliance with industry regulations and avoid potential legal issues.
- Sustainability: efficient fuel management practices contribute to a more sustainable approach to resource utilisation, reducing the environmental impact associated with excessive fuel consumption and wastage.
- Enhanced security: preventing fuel theft not only protects your financial assets but also enhances the overall security of your fleet, ensuring the safety of both your vehicles and your drivers.

3.6. Fuel theft trends

There are many tactics criminals use when stealing fuel from a vehicle, you might be familiar with syphoning, the traditional method of fuel theft where criminals use plastic tubing to syphon fuel from work vehicles and pour it into a petrol can for personal use, but you might not know the other popular methods of fuel theft such as:

- Fuel tank puncturing: there has been a growing trend of thieves puncturing fuel tanks, particularly in businesses with parked car fleets overnight. This technique allows for quicker fuel extraction in larger quantities but often results in considerable vehicle damage and costly repairs.
- Damaging fuel caps and fuel lines: criminals might resort to breaking petrol caps or cutting fuel lines as another means of gaining access to the fuel within the tank.
- Misuse of fuel cards: employees may sometimes swipe the business card for personal use or lend their fuel cards to friends or family resulting in unauthorised

transactions. Tellers may also swipe fuel cards more than once reflecting in duplicate transactions and double the fuel costs.

- Cloning of fuel cards: similar to credit card cloning, fuel cards can be duplicated, often going undetected by banks until it’s too late.
- Illegally accessing pipelines: in more complex scenarios, criminals may illegally tap into fuel pipelines to syphon off significant volumes of fuel. This is a technique commonly seen within the oil and fuel industry.

CHAPTER 4

ANALYSIS OF EXISTING AIRCRAFT FUEL MEASURING SYSTEMS

4.1. Basic fuel measuring systems (FMSs) based on measurement sensors

The primary methods for fuel level measurement in aircraft include:

- Measuring system based on float-type gauges : these gauges use a float connected to a mechanical linkage or potentiometer that moves with the fuel level. As the fuel level changes, the position of the float changes, which is then translated into an electrical signal or displayed directly on a cockpit gauge.
- Measuring system based on capacitance-type sensors : capacitance-type fuel level sensors consist of conductive probes inserted into the fuel tanks. The capacitance between the probe and the tank wall changes as the fuel level rises or falls. This change in capacitance is measured and converted into a fuel level indication.
- Measuring system based on ultrasonic sensors : ultrasonic fuel level sensors use ultrasonic waves to measure the distance between the sensor and the surface of the fuel. By measuring the time it takes for the ultrasonic waves to bounce off the fuel surface and return to the sensor, the fuel level can be accurately determined.
- Measuring system based on pressure sensors : in some aircraft, pressure transducers are used to measure the hydrostatic pressure exerted by the fuel in the tanks. This pressure is directly proportional to the fuel level and can be converted into a fuel quantity indication.
- Measuring system based on radioisotope sensors : a radioisotope fuel level sensor is a device that utilizes radioactive materials to measure the level of fuel in a tank.
- Digital fuel quantity fauging systems : modern aircraft often utilize digital fuel quantity gauging systems that integrate inputs from multiple sensors and probes to provide accurate fuel quantity indications to the flight crew. These systems

typically employ redundant sensors and sophisticated algorithms to ensure reliability and accuracy.

- Fuel flow meter : this is used to measure the volumetric fuel consumption. It connects to the fuel line between the tank and the engine.

In addition to these primary methods, aircraft may also incorporate secondary or backup systems for fuel level measurement to enhance safety and redundancy. These backup systems may include manual dipsticks, visual sight gauges, or alternative electronic sensors.

Overall, the combination of these methods ensures that aircraft have reliable and accurate fuel level measurements, which are critical for flight planning, fuel management, and overall safety.

4.2. Analysis of the fuel measuring system (FMS) based on float type sensors

The simplest fuel gauges are float gauges. The principle of their operation is based on the use of the pushing force of the liquid (fuel) acting on the float. The float is rigidly fixed on one of the arms of the lever. The output parameter of the sensor is the angle of rotation of the free end of the lever. The working range of rotation of the lever is about 90 degrees.

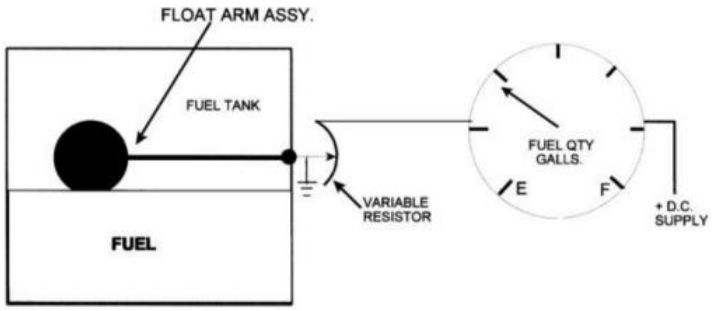

Fig.4.1.Fuel measuring system based on simplest float gauge

These sensors are usually made of a floating material, such as foam, that floats on the surface of the fuel. When the fuel level drops, the float lowers, which changes the position of the contact, which, in turn, sends a signal to the fuel gauge.

There are the following types of float fuel gauges. They are classified by fuel level sensors :

- Float resistive fuel level sensor. As a rule, such fuel level sensors are standard (installed during the production of the vehicle) and according to the principle of operation, they are resistive: the position of the float determines the output resistance of the fuel level sensor.
- Float reed switch fuel level sensor. Fuel level measurement is achieved by sliding the magnetic float to the length of the measuring line (guide tube), in which reed switches and resistors connected according to the resistive divider scheme are installed. Closing the reed switch changes the resistance, the value of which can be converted into an analog or digital output signal.
- Float magneto-strictive fuel level sensor. The measurement of the value of the fuel level sensor is achieved by sliding the magnetic float along the length of the measuring ruler (guide tube), in which a magnetic alloy string is stretched. The principle of measuring the position of the float is based on the magnetostriction effect.

Advantages and disadvantages simplest fuel float gauge :

- Advantages : the advantages of float gauges include their simplicity, reliability and the possibility of use in a variety of conditions.
- Disadvantages : float gauges may require regular maintenance to ensure their reliability and accuracy. This includes cleaning from dirt, lubricating the mechanism and checking all elements.

Advantages and disadvantages float resistive fuel level sensor :

- Advantages : simplicity of construction; low cost.
- Disadvantages : inaccuracy of fuel level measurement when maneuvering the aircraft, large measurement error from 10 to 30% of the fuel content, mechanical wear.

Advantages and disadvantages float reed switch fuel level sensor :

- Advantages : simplicity of construction; low cost.
- Disadvantages : mechanical wear.

Advantages and disadvantages float magnetostrictive fuel level sensor :

- Advantages : very high measurement accuracy.
- Disadvantages : high cost (2000 $) , the design of the sensor does not make it possible to use it on vehicles.

Conclusion : The significant disadvantages of such a fuel gauge are its lack of distance and the fact that it measures the level of the liquid, not its mass. The additional error of the lever-float level gauge sensor is caused by the deviation from the calculated value of the medium temperature and is caused by the temperature change in the density of the liquid and vapor-gas mixture, the change in the volume. The main error of such fuel gauges is (4-6) % of the maximum fuel reserve.

4.3. Analysis of the fuel measuring system (FMS) based on ultrasonic sensors

In acoustic level meters, the current position of the level is determined by the time of passage of ultrasonic vibrations from the source to the receiver when reflected from the interface of two environment (media) .

The location of the level is most often carried out from below, and at the same time the thickness of the liquid layer above the source and receiver of ultrasonic vibrations is determined. The location from below is better, since in this case the source and receiver work in more favorable conditions, which requires low power of the source of oscillations and low amplification in the receiving part of the device. Most ultrasonic level meters have single-element sensors that perform the functions of emitter and receiver and a reflective surface of the level that ensures the arrival of the reflected signal to the receiver.

Principle of operation: ultrasonic fuel level sensors work by emitting ultrasonic waves from a transducer mounted on the top of the tank. These waves travel through the air and reflect off the surface of the fuel. The sensor then calculates the distance to the fuel surface based on the time it takes for the ultrasonic waves to travel to the fuel and back. This distance measurement is used to determine the fuel level in the tank.

Advantages and disadvantages fuel ultrasonic sensor :

- Advantages : one of the main advantages of ultrasonic fuel level sensors is that they provide non-contact measurement. They do not require direct contact with the fuel, which reduces the risk of contamination and allows for installation in tanks with complex shapes or hazardous materials. Ultrasonic fuel level sensors can offer high accuracy in measuring fuel levels, particularly when properly calibrated and installed.

- Disadvantages : high cost (2000 $), inaccuracy of fuel level measurement when maneuvering the aircraft, Fluctuations in the surface of the fuel in the tank will lead to the fact that the reflected signal may not hit the receiver. The accuracy may be affected by factors such as temperature variations, the presence of foam or vapor above the fuel surface, and the tank's shape and material.

Conclusion : a system based on ultrasonic fuel level sensors is not suitable for measuring fuel in an aircraft in a horizontal position and even more so during its maneuvering. This is due to the fact that the fluctuation of the fuel surface in the tank will lead to the fact that the reflected signal may not reach the receiver and this is catastrophically unacceptable during flight.

Fig.4.2. Ultrasonic fuel sensors

4.4. Analysis of the fuel measuring system (FMS) based on radioisotope sensor

These sensors emit radiation towards the fuel surface and then detect the radiation that is either reflected or transmitted back. The amount of radiation detected corresponds to the level of fuel in the tank.

Principle of operation: radioisotope fuel level sensors work on the principle of radiation attenuation. Radioactive isotopes emit radiation, which interacts with the fuel in the tank. The amount of radiation detected by the sensor depends on the thickness or density of the fuel between the radiation source and the detector. As the fuel level changes, the amount of radiation detected also changes, allowing the sensor to determine the fuel level.

Advantages and disadvantages fuel ultrasonic sensor :

- Advantages : one of the advantages of radioisotope fuel level sensors is that they can provide non-contact measurement of fuel levels. They do not require direct contact with the fuel, which can be useful in applications where direct contact is impractical or undesirable. Radioisotope fuel meters can provide high measurement accuracy. Many radioisotope fuel gauges have a long service life because the isotopes decay slowly. This allows them to be used for a long time without the need for frequent replacement or maintenance.
- Disadvantages : the disadvantage of such level gauges is that radiation affects the quality of fuel and is dangerous for humans. Inaccuracy of fuel level measurement when maneuvering the aircraft. The use of radioactive materials in these sensors raises safety concerns. Proper shielding and containment measures must be in place to ensure that radiation exposure to personnel and the environment is minimized. Additionally, regulatory requirements for the handling, storage, and disposal of radioactive materials must be followed.

Conclusion : despite these advantages, it is also important to consider the potential risks associated with the use of radioactive materials, such as the safety of handling, storage and disposal of waste. Radioisotope fuel gauges pose a threat to human health.

4.5. Analysis of the fuel measuring system (FMS) based on capacitance-type sensors

Capacitive fuel level sensors are devices that use the principle of capacitance to measure the fuel level in the tank.

Principle of operation : capacitance-type fuel level sensors work by measuring the change in capacitance between two electrodes as the fuel level in the tank changes. Typically, one electrode is mounted at the top of the tank, and another is mounted at the bottom or immersed in the fuel. The capacitance between these electrodes changes as the dielectric material (fuel) between them changes, allowing the sensor to determine the fuel level.

Advantages and disadvantages fuel capacitance sensor :

- Advantages : capacitance-type fuel level sensors can offer high accuracy in measuring fuel levels, particularly when properly calibrated and installed. They can provide precise measurements even in challenging conditions, such as when the fuel is sloshing or when there are variations in temperature. These sensors are versatile and can be used in various types of tanks, including above-ground and underground tanks, as well as tanks containing different types of fuels such as gasoline, diesel, or aviation fuel. Capacitance-type fuel level sensors can offer a cost-effective solution for measuring fuel levels, particularly for applications where high accuracy and reliability are required.
- Disadvantages : the disadvantages of the scheme include the low accuracy of measuring small values of capacitances, so sensors with an increased number of electrodes (tubes) have to be used, which finally leads to a new disadvantage - an increase in the size and weight of the sensor.

Conclusion : capacitance fuel level sensors offer accurate and reliable measurement of fuel levels in tanks across various applications. Their robust construction, compatibility with different fuels, and versatility make them valuable tools for monitoring fuel levels in aviation.

Fig.4.3. Capacitive fuel sensors

4.6. Digital fuel quantity fauging systems

Digital fuel quantity gauging systems use various types of sensors to measure the fuel level in the tank. These sensors can include capacitance sensors, ultrasonic sensors, pressure sensors, or even traditional float sensors with digital interfaces.

Principle of operation: the raw data from the sensors is processed by a digital control unit or module. This module may include microcontrollers or other processing units capable of converting the sensor readings into digital data. The digital fuel quantity gauging system provides output in digital format, which can be displayed on a digital screen or transmitted to other systems via digital communication protocols such as CAN bus or Ethernet. This allows for easy integration with other onboard systems in vehicles or industrial machinery.

Advantages and disadvantages digital fuel quantity fauging systems :

- Advantages : digital fuel quantity gauging systems are known for their accuracy and precision in measuring fuel levels. They often undergo calibration procedures to ensure accurate readings across the full range of fuel levels and under various operating conditions. Many digital fuel quantity gauging systems offer advanced features beyond simple fuel level measurement. These can include fuel consumption monitoring, range estimation, low fuel warnings, and integration with navigation or fleet management systems.
- Disadvantages : while digital fuel quantity gauging systems offer many benefits, they may be more expensive and complex to install and maintain compared to traditional analog systems. However, the advantages in accuracy, features, and integration capabilities often justify the investment, especially in high-demand applications.

Conclusion : Digital fuel quantity gauging systems may include diagnostic features to monitor the health and performance of the system components. This can help identify and address any issues or malfunctions that may arise. These systems can often be customized to suit specific applications and integrated with other onboard systems, such as engine management systems, to provide comprehensive fuel monitoring and management capabilities digital fuel quantity gauging systems may include diagnostic features to monitor the health and performance of the system components.

Fig.4.4.Digital fuel quantity fauging systems aircraft A320

4.7. Fuel flow meter

The flow meters used for fuel consumption measurement are primarily of differential type flow meters. It has two measuring chambers – one for the supply fuel line and the other for the return fuel line. It measures volumetric fuel consumption by computing the difference between the consumption in supply and return line.

Principle of operation : fuel flow meters in aircraft typically use turbine or mass flow measurement principles to determine the amount of fuel being used. Turbine-based fuel flow meters consist of a turbine rotor placed in the path of the fuel flow. As the fuel flows through the meter, it causes the turbine rotor to rotate, and the rotational speed is directly proportional to the flow rate of the fuel.

Advantages and disadvantages fuel flow meter :

- Advantages : high Precision . Their accuracy is not affected by moisture and temperature. Transmits the fuel consumption directly unlike fuel level sensors where the consumption needs to be calculated based upon the fuel level.
- Disadvantages : the meter requires periodic maintenance because the moving parts of the meter leads to the wear and tear of the parts. The installation of these

meters is difficult as modifications in the fuel line are required for the same. The dirt filter needs to be checked and changed cleaned periodically. Costlier when compared to fuel level sensors. Can’t be used for measuring the fuel level in the tank.

Conclusion : the fuel flow meter provides critical information to pilots and flight crew, allowing them to monitor fuel consumption, manage fuel reserves, and ensure the safe operation of the aircraft. Accurate fuel flow measurement is essential for flight planning, fuel management, and maintaining the aircraft's performance within safe limits.

Fig.4.5.Fuel flow meters

4.8. Analysis of the fuel measuring system (FMS) based on pressure sensors

In an aircraft fuel tank, a hydrostatic sensor, typically a pressure transducer, serves a critical role in monitoring fuel levels and ensuring the safety and efficiency of the aircraft's fuel system.

Principle of operation : the hydrostatic sensor, often a pressure transducer, is installed at a strategic location within the fuel tank. This location is typically at the lowest point of the tank to ensure accurate measurement of the hydrostatic pressure exerted by the fuel. The hydrostatic sensor measures the pressure exerted by the fuel column above it. This pressure is directly proportional to the height of the fuel column and is known as hydrostatic pressure. As the fuel level changes, the hydrostatic pressure detected by the sensor also changes.

Advantages and disadvantages fuel pressure sensor :

- Advantages : hydrostatic sensors provide precise measurements of fuel levels by directly detecting the hydrostatic pressure exerted by the fuel column in the tank. This accuracy allows pilots and flight crew to have a clear understanding of the remaining fuel quantity, enabling better fuel management decisions. Hydrostatic sensors enable sophisticated fuel management systems in modern aircraft. These systems can automatically distribute fuel between tanks to maintain balance and stability, optimizing aircraft performance and handling characteristics. Hydrostatic sensors are designed to withstand the harsh operating conditions within aircraft fuel tanks, including temperature variations, vibrations, and exposure to fuel vapors. They are built to be highly reliable, providing accurate measurements consistently over time. Hydrostatic sensors are compatible with various types of aircraft and fuel systems, making them versatile solutions for fuel level monitoring across different aircraft models and configurations.
- Disadvantages : implementing hydrostatic sensors in aircraft fuel systems adds complexity to the overall system. This complexity involves sensor installation, integration with existing avionics systems, calibration procedures, and maintenance requirements. More complex systems may increase the potential for errors or malfunctions. Maintenance Requirements: hydrostatic sensors require regular maintenance to ensure accurate and reliable performance. This maintenance includes periodic calibration checks, inspection for damage or corrosion, and replacement of components as needed. Maintenance procedures may require specialized equipment and trained personnel, adding to operational costs.

Conclusion : in summary, the use of hydrostatic sensors in aircraft fuel tanks offers numerous benefits, including accurate fuel level measurement, real-time monitoring, enhanced safety, fuel efficiency, advanced fuel management capabilities, early warning systems, reliability, and compatibility with diverse aircraft systems. These advantages contribute to safer, more efficient, and cost-effective flight operations.

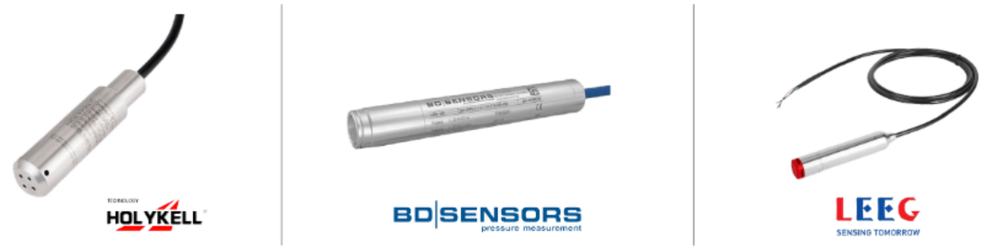

Fig.4.6. Pressure sensors

4.9. How to choose the right fuel sensor

To choose between the listed fuel sensors, you need to know :

- Tank dimensions (primarily height). The height and shape of the tank play a crucial role for the fuel level sensors. Make sure the client provides this data (at least roughly) before installing.
- The measuring part of the sensor must be slightly bigger than the tank height (to make sure the sensor reaches fuel at the bottom of the tank). During installation the measuring tubes will be cut to fit the tank. However, it is important to leave a gap of 1-1.5 inches (3-4 cm) between the sensor and the bottom to prevent a short circuit due to possible dirt or water accumulation at the tank bottom.

4.10. Location of multiple fuel gauges on an aircraft

One might need to consider a few fuel sensors for one aircraft, if it falls into one of the following cases:

- The aircraft has two or more fuel tanks. Generally, a heavy-duty aircraft will have two or more fuel tanks. Installing a fuel sensor on each tank will provide a full picture of the fuel level. In a GPS tracking system it can be displayed separately for each sensor and as an aggregate value of all the fuel sensors.
- The fuel tank of the aircraft has a complex shape. As it is often the case with aviation equipment, a fuel tank might have a customized shape or consist of two different sections. In this case, it requires two or more fuel sensors to provide for precise measurements. The GPS tracking and telematics system will show an average value of all the fuel sensors.

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Fuel tankers have 2 or 3 tanks, each of them having at least 3 sections. For maximum accuracy each tank and each section should be equipped with a fuel level sensor.

4.11. Comparison of fuel remaining measurement methods

Based on the described fuel measurement methods, a comparative table was created :

Table 1

Comparison Chart					
Sensors Characteristics	**Resistive/ Float Sensors**	**Pressure Sensors**	**Capacitive Sensors**	**Ultrasonic Sensors**	**Flow**
Cost	Low	Low	Medium	Medium	High
Installation	Medium	Easy	Medium	Easy	Difficult
Maintenance	Medium	Low	Low	Low	Medium
Temperature & Humidity	Not Affected	Not Affected	Affected	Easily Affected	Not Affected
Accuracy	~ 80-85 %	~ 95 %	~ 99 %	>99 %	>99%

4.12. Conclusion for aircraft fuel metering systems (FMS)

Conclusion : The analysis of existing widespread fuel measuring systems (FMS) of aircraft using float and capacitive fuel level sensors shows that these systems measure fuel level in aircraft tanks with sufficient accuracy only in horizontal flight. During aircraft evolutions, the measurement of fuel residue in such FMS leads to significant methodological errors. In addition, they have a rather complex electromechanical design and significant mass-size characteristics, which together affects overall reliability of such vehicles as a whole. Therefore, studies aimed at the development of fuel measurement systems minimizing such methodological errors are very relevant.

CHAPTER 5
ANALYSIS OF THE PRESSURE SENSOR

5.1. What is a hydrostatic pressure sensor (HPS)

A hydrostatic pressure sensor is a device that measures the pressure of a liquid by determining the force that the liquid exerts on a sensor placed at a certain depth. These sensors are used in a variety of applications, including measuring the level of liquid in a tank, monitoring water pressure in pipelines, and measuring water depth in oceans, lakes, or rivers.

5.2. Hydrostatic pressure sensor (HPS) history

The history of hydrostatic pressure sensors dates back to the 17th century when the Italian physicist Evangelista Torricelli discovered that atmospheric pressure could be measured by inverting a tube filled with mercury into a pool of mercury. This invention, known as the “barometer”, provided the basis for measuring pressure in fluids.

The first hydrostatic pressure sensor was developed in the early 20th century, with the invention of the “strain gauge” by Edward E. Simmons and Arthur C. Ruge in 1938.

The strain gauge is a device that measures the deformation of a material under stress, and it is commonly used in pressure sensors to convert the physical pressure of a fluid into an electrical signal.

During World War II, hydrostatic pressure sensors were used in military applications, such as measuring the depth of submarines and torpedoes. After the war, the use of hydrostatic pressure sensors expanded to other industries, including oil and gas, water management, and environmental monitoring.

In the 1970s, the development of microelectronics led to the miniaturization of hydrostatic pressure sensors, making them smaller, more accurate, and more affordable. This led to the widespread adoption of hydrostatic pressure sensors in various applications, including automotive, medical, and consumer electronics.

Today, hydrostatic pressure sensors are widely used in a variety of industries and applications, and they continue to evolve with advances in technology, such as the development of wireless sensors and Internet of Things (IoT) connectivity.

5.3. Hydrostatic pressure sensor (HPS) performance

Hydrostatic pressure sensors are designed to provide accurate and reliable measurements of liquid pressure and level, with a high degree of sensitivity and stability over time. The performance of a hydrostatic pressure sensor depends on several factors, including the design, materials, and operating conditions.

Here are some of the key performance metrics of hydrostatic pressure sensors:

- Accuracy: the accuracy of a pressure sensor refers to how closely its measured values match the true values. Hydrostatic pressure sensors are typically designed to have high accuracy, with a range of ±0.1% to ±0.5% of full scale.
- Sensitivity: the sensitivity of a pressure sensor refers to the smallest change in pressure that it can detect. Hydrostatic pressure sensors have high sensitivity, with a range of 0.05% to 0.1% of full scale.
- Linearity: the linearity of a pressure sensor refers to how well it follows a straight line when measuring pressure. Hydrostatic pressure sensors are designed to have high linearity, with a range of ±0.1% to ±0.3% of full scale.
- Stability: the stability of a pressure sensor refers to how well it maintains its calibration over time. Hydrostatic pressure sensors are designed to have high stability, with long-term drift rates of less than 0.1% per year.
- Temperature sensitivity: the temperature sensitivity of a pressure sensor refers to how much its output changes with temperature. Hydrostatic pressure sensors are designed to have low-temperature sensitivity, with compensation for temperature changes.
- Response time: the response time of a pressure sensor refers to how quickly it can respond to changes in pressure. Hydrostatic pressure sensors typically have fast response times, with a range of a few milliseconds to a few seconds.

5.4. Hydrostatic pressure sensor (HPS) accuracy

The accuracy of a hydrostatic pressure sensor is an important characteristic that determines the reliability and usefulness of the sensor. The accuracy of a hydrostatic pressure sensor refers to the degree to which the sensor's output reading reflects the actual pressure being measured.

The accuracy of a hydrostatic pressure sensor is expressed as a percentage of the full-scale range (FSR) of the sensor. For example, if a sensor has a full-scale range of 10,000 psi and is accurate to within 0.1% of FSR, then its accuracy is ±10 psi.

The accuracy of a hydrostatic pressure sensor can be affected by various factors, including temperature, humidity, and mechanical stress. Some factors that can affect the accuracy of a hydrostatic pressure sensor include :

- Non-linearity: the sensor may not produce a linear response to changes in pressure, causing inaccuracies in the output.
- Hysteresis: the sensor's output may differ depending on whether the pressure is increasing or decreasing, causing inaccuracies in the output.
- Temperature effects: temperature changes can affect the accuracy of the sensor, causing it to drift from its calibrated state.
- Long-term stability: over time, the sensor's output may drift from its calibrated state due to aging, environmental factors, and other factors.

The accuracy of hydrostatic pressure sensors varies depending on the type of sensor and the application. High-end sensors can have accuracies as low as 0.1% of FSR, while lower-end sensors may have accuracies of 1-2% of FSR or higher. The required accuracy for a given application depends on the level of precision required and the consequences of inaccurate readings.

5.5. Hydrostatic pressure sensor (HPS) types

Hydrostatic pressure sensors are occasionally called "submersible pressure transmitters" if they are submerged. Different types of submersible pressure transmitter are as below:

- Sealed gauge submersible pressure transmitter. Sealed gauge pressure transmitters are designed to measure the pressure of a liquid relative to atmospheric pressure, but with the reference sealed. This means that the reference pressure inside the transmitter is fixed at atmospheric pressure, which eliminates the effects of changes in atmospheric pressure on the measurement. Sealed gauge pressure transmitters are ideal for applications where the hydrostatic pressure will remain relatively stable.
- Vented gauge submersible pressure transmitter. Vented gauge pressure transmitters are similar to sealed gauge pressure transmitters, but with a vented reference. This means that the reference pressure inside the transmitter is vented to the atmosphere, which allows for changes in atmospheric pressure to be compensated for in the measurement. Vented gauge pressure transmitters are ideal for applications where the hydrostatic pressure will vary with changes in atmospheric pressure.
- Absolute submersible pressure transmitter. Absolute pressure transmitters are designed to measure the pressure of a liquid relative to a perfect vacuum, or zero pressure. Absolute pressure transmitters are used in applications where the hydrostatic pressure is high enough that it exceeds atmospheric pressure, or where the reference pressure needs to be fixed at zero.

5.6. Submersible pressure transmitter installation

Installing a submersible pressure transmitter requires careful consideration to ensure accurate and reliable measurements. Here are some key considerations that must be taken into account:

- Mounting: the transmitter should be mounted in a secure and stable location to prevent movement or vibration that can affect the accuracy of the measurement. It is important to ensure that the sensing element is in direct contact with the liquid to be measured.

- Cable: the cable connecting the transmitter to the control system should be securely fastened and protected from damage. It should be long enough to reach the control system, but not too long as this can cause signal degradation.
- Cable routing: the cable should be routed in a manner that prevents any potential damage from sharp edges or other hazards. It should be protected from exposure to water and other environmental factors.
- Calibration: the transmitter should be calibrated prior to installation to ensure accurate measurement of the hydrostatic pressure. It is recommended to perform a zero and span calibration to account for any errors in the measurement.
- Environmental factors: the environmental factors, such as temperature and atmospheric pressure, can affect the accuracy of the measurement. The transmitter should be installed in an area where these factors can be controlled or accounted for.
- Electrical grounding: proper electrical grounding should be provided to ensure the safety of the equipment and personnel. It is recommended to follow the manufacturer's instructions for proper grounding.
- Maintenance: regular maintenance and inspection should be performed to ensure the transmitter continues to provide accurate and reliable measurements. This includes checking for any damage to the cable or sensing element, verifying the calibration, and cleaning the sensor if necessary.

By considering these factors and following the manufacturer's instructions for installation and operation, a submersible pressure transmitter can provide accurate and reliable measurement of hydrostatic pressure for a wide range of applications.

5.7. Hydrostatic pressure sensor (HPS) applications

Hydrostatic pressure sensors are used in a wide range of applications where precise and reliable pressure measurement is required. Some common applications of hydrostatic pressure sensors include :

- Industrial process control: hydrostatic pressure sensors are used to measure pressure in various industrial processes, such as chemical processing, oil and gas production, water treatment and tank level measurement.
- HVAC systems: hydrostatic pressure sensors are used to measure the pressure in heating, ventilation, and air conditioning (HVAC) systems to ensure efficient operation and maintain a comfortable indoor environment.
- Aerospace and aviation: hydrostatic pressure sensors are used in aircraft and spacecraft to measure air pressure, altitude, and other critical parameters.
- Medical devices: hydrostatic pressure (HP) sensors are used in medical devices such as blood pressure monitors, respiratory equipment, and dialysis machines.
- Automotive: hydrostatic pressure sensors are used in automotive applications such as tire pressure monitoring systems, fuel injection systems, and engine control systems.
- Marine and underwater: hydrostatic pressure sensors are used in marine and underwater applications such as submersibles, underwater vehicles, and offshore drilling equipment.
- Environmental monitoring : hydrostatic pressure sensors are used in environmental monitoring applications such as weather forecasting, flood warning systems, and water level monitoring.
- Research and development: hydrostatic pressure sensors are used in scientific research and development applications such as geology, oceanography, and materials science to study the behavior of materials and fluids under high pressure.

Overall, hydrostatic pressure sensors are widely used in various industries and applications where precise and reliable pressure measurement is essential for safe and efficient operation.

5.8. Hydrostatic pressure sensor (HPS) calibration

Calibration is an important aspect of maintaining the accuracy and reliability of hydrostatic pressure sensors. Calibration is the process of comparing the output of the sensor to a known reference value and adjusting the sensor to correct any discrepancies between the two.

Hydrostatic pressure sensors can be calibrated using various methods, including:

- Deadweight tester: a deadweight tester is a device that applies a known weight to a piston, which in turn applies pressure to the sensor being calibrated. The pressure generated by the weight is measured using a reference pressure gauge, and the output of the sensor is adjusted accordingly.
- Pressure comparator: a pressure comparator is a device that generates precise and stable pressure using a piston and hydraulic system. The pressure generated by the comparator is compared to the output of the sensor being calibrated, and the output of the sensor is adjusted accordingly.
- Automated calibration system: automated calibration systems use software and hardware to automate the calibration process, making it faster and more efficient. These systems can be used to calibrate multiple sensors simultaneously and can generate calibration certificates and reports.

Hydrostatic pressure sensors should be calibrated regularly to ensure that they are operating accurately and within their specified range. The frequency of calibration depends on the application and the requirements of the regulatory bodies or standards organizations that apply. It is also important to ensure that the calibration process is performed by trained and qualified personnel using appropriate equipment and procedures.

5.9. Advantages and disadvantages of using hydrostatic pressure sensors (HPSs)

Advantages of using hydrostatic pressure sensors include :

- Accurate and precise measurements : hydrostatic pressure sensors provide accurate and precise measurements of fluid pressure, making them ideal for use in applications where precise pressure measurement is critical.
- Simple and reliable : hydrostatic pressure sensors are relatively simple in design and do not contain any moving parts, which makes them more reliable and less prone to failure than other types of pressure sensors.

- Can be used in harsh environments : hydrostatic pressure sensors are designed to withstand harsh environments, including high temperatures, high pressures, and corrosive substances.
- Low power consumption : hydrostatic pressure sensors typically have low power consumption, which makes them suitable for use in battery-powered or remote applications.

Disadvantages of using hydrostatic pressure sensors include :

- Limited pressure range: hydrostatic pressure sensors are typically limited to measuring pressures within a certain range, which may not be suitable for all applications.
- Temperature sensitivity: hydrostatic pressure sensors can be sensitive to temperature changes, which can affect the accuracy of the measurements.
- Calibration: hydrostatic pressure sensors require regular calibration to ensure accurate readings, which can be time-consuming and expensive.
- Cost: hydrostatic pressure sensors can be more expensive than other types of pressure sensors, particularly if they are designed for use in harsh environments.
- Installation: hydrostatic pressure sensors require careful installation and positioning to ensure accurate readings, which can be challenging in certain applications.

5.10. Conclusion for hydrostatic pressure sensors (HPSs)

Conclusion : hydrostatic pressure sensors are a type of pressure sensor that measures the pressure of a fluid by measuring the weight of the fluid above the sensor. These sensors are widely used in many industries, including water treatment plants, chemical plants, oil and gas pipelines, and marine environments. The advantages of using hydrostatic pressure sensors include accurate and precise measurements, simplicity and reliability, a wide range of applications, the ability to withstand harsh environments, and low power consumption. However, the disadvantages include limited pressure range, temperature sensitivity, regular calibration requirements, high cost, and challenges with installation and positioning. Overall, hydrostatic pressure sensors are a reliable and effective solution for measuring fluid pressure in a variety of applications, but the specific advantages and disadvantages of using these sensors will depend on the specific needs and requirements of the application.

CHAPTER 6

FUEL LEVEL DURING AIRCRAFT MOVEMENT

6.1. Location of fuel in the aircraft during flight

In most large aircraft, the fuel is stored in the wings, although some aircraft also have tanks in the center body, or the center fuselage, called center tanks. Additionally, widebody aircraft have extra tanks in the tail or the horizontal stabilizer, which are used to control the center of gravity of the aircraft during long-haul flights.

The storage of fuel in the wings helps to prevent wing bending stresses. Due to this reason, wing tank fuel is used last during the course of the flight. For example, if an aircraft has a center tank, the center tank fuel is used first before the fuel is drained from the wings.

Also, in larger aircraft, the wing tank is divided into an outer and inner tank. In this case, the inner tank fuel is used before the fuel from the outer tank is used. This again helps to relieve stresses on the wing.

In addition to the storage tanks, there are tanks present in the fuel system known as surge tanks, which are also a part of the fuel vent system. All the main fuel tanks in the aircraft are connected to the surge tank through a vent pipe.

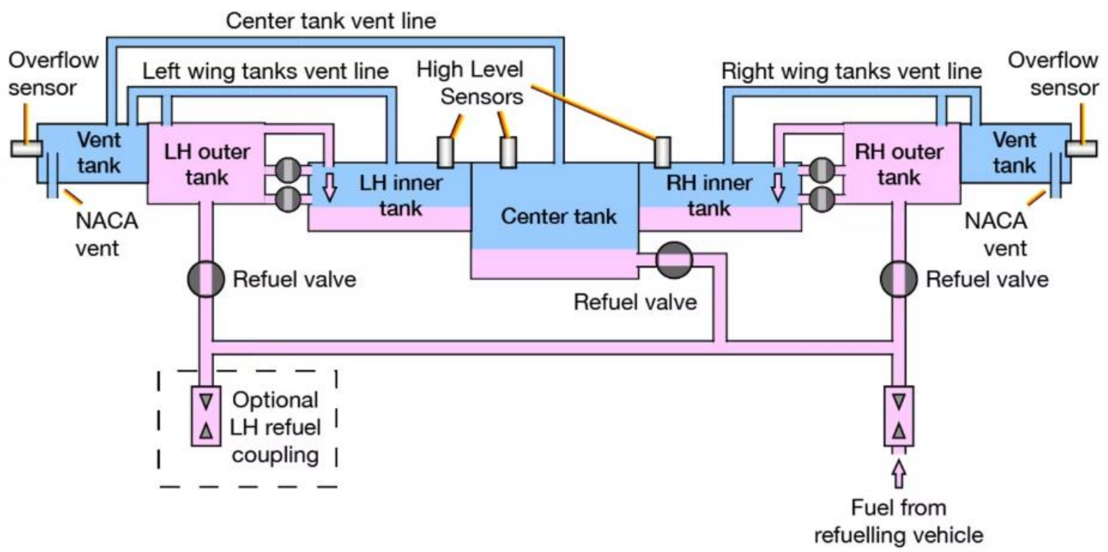


Fig.6.1. Functional schematic of the location of fuel in the aircraft

6.2. Fuel movement during aircraft maneuvering

During aircraft maneuvering, any fuel that moves out of the tanks falls into the surge tank through the vent pipe. Subsequently, when the aircraft levels off, the fuel from the surge tank is gravity-fed back to the main tanks.

6.3. Float and capacitive fuel level sensors (FLSs) during flights

The known methods of measuring the fuel level in the tanks of modern aircraft using float and capacitive fuel level sensors do not allow to determine its residue during maneuvering, when pitch and roll angles undergo significant changes. In the conditions of maneuvering flight the methodical error increases significantly, which during prolonged maneuvering can lead to undesirable consequences. In order to obtain stable fuel residue readings for the above reasons, it is necessary to use new approaches to the construction of the measuring system of fuel residue in the tanks of the aircraft with high reliability, as well as with the minimum mass and dimensional dimensions.

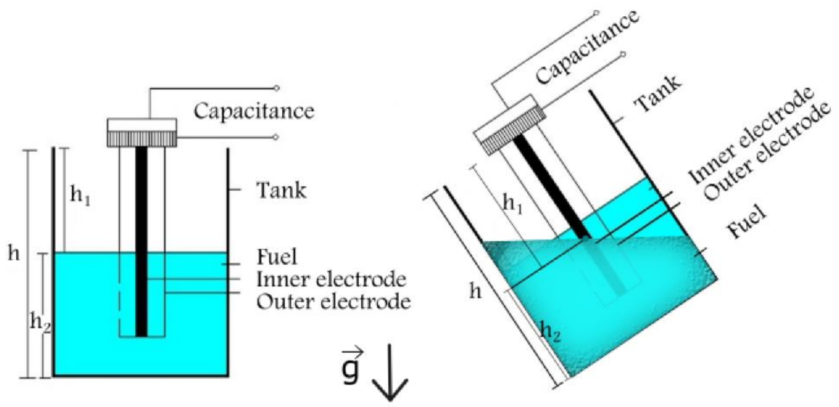


Fig.6.1. Capacitive sensor during aircraft maneuvering

6.4. Aircraft flight dynamics

Flight dynamics is the science of air vehicle orientation and control in three dimensions. The three critical flight dynamics parameters are the angles of rotation in three dimensions about the vehicle's center of gravity (CG), known as pitch, roll and yaw(Eueler Angels). That is, the movement of the aircraft in space during its maneuvering occurs at three angles :

- Pitch.

- Roll.
- Yaw.

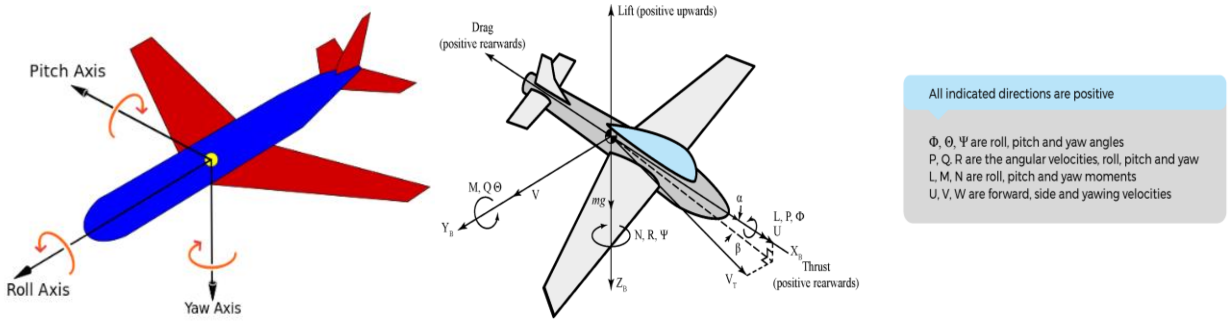


Fig.6.2. Typical aeronautical Euler Angles

6.5. Solving the problem of fuel level measurement during aircraft movement

6.5.1. Principle of FMS operation on the basis of HPS

Let us consider the principle of FMS operation on the basis of hydrostatic pressure sensors (HPS) on the example of determining the volume of fuel in the tank of an aircraft made in the form of a parallelepiped with edges a, b, c with fuel "mirror height" h_{fm} (Fig.6.3). The base of the parallelepiped is tied to the horizontal geotopic triangle OENH, which in this case is considered as an instrumental one. The angles of heading Ψ, pitch θ and roll Y of the aircraft are assumed for this case to be zero.

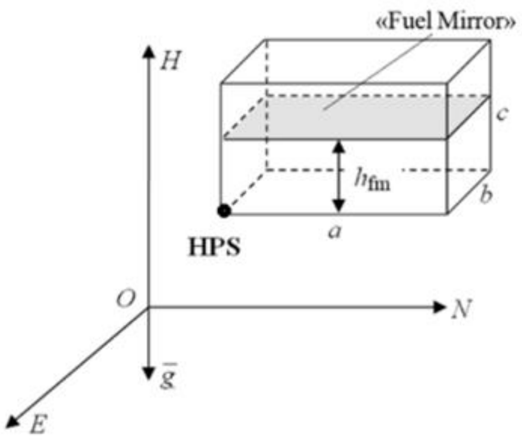


Fig.6.3. Mirror height

According to the readings of the HPS, which is located in one of the vertices of the base of the parallelepiped, we can calculate the height of the "fuel mirror" (FM) plane h_{fm}. According to Pascal's law

$$P_{h_{\text{fm}}} = \rho \cdot g \cdot h_{\text{fm}}; \qquad h_{\text{fm}} = P_{h_{\text{fm}}} / (\rho \cdot g), \tag{1}$$

where $P_{h_{fm}}$ is hydrostatic pressure of a liquid with constant density in homogeneous field of gravity: ρ is the density of the liquid; g is the acceleration of free fall .The volume of fuel in the tank $V_{h_{fm}}$ at height h_{fm} is calculated from the formula of parallelepiped volume:

$$V_{h_{fm}} = abc = abh_{fm}. \tag{2}$$

6.5.2. Design of the fuel tank and determination of its volume

Modern designs of aircraft fuel tanks are usually located in the wings and fuselage of the airplane and have shapes close to a parallelepiped. To solve the problem of determining the fuel volume in each of the tanks, it is proposed to divide its space into inscribed volume figures, the fuel volume in which can be calculated separately, and the total fuel volume can be found as the sum of the fuel volumes of the figures inscribed in the tank. In this diplom work, the tetrahedron (T) is considered as an inscribed volume figure.

For example, let us consider the possibility of partitioning a parallelepiped into tetrahedrons. The parallelepiped, as can be seen from Fig.6.4, is partitioned into four tetrahedrons :

- tetrahedron 1, with vertices: 1, 3, 4, 8;
- tetrahedron 2, with vertices: 1, 2, 3, 6;
- tetrahedron 3, with vertices: 3, 6, 7, 8;
- tetrahedron 4, with vertices: 1, 5, 6, 8.

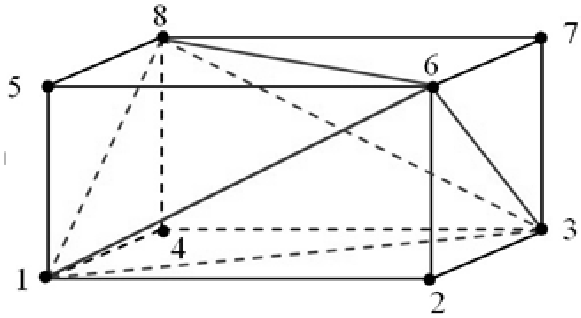


Fig.6.4. Partitioning a parallelepiped into tetrahedrons

Fuel residue volume V_x for tetrahedron No.2 with vertices 1, 2, 3, 6 (Fig.6.5) in the coordinate system of the instrument trihedron *ONEH* and HPS located in one of the base vertices can be determined from the following relations:

- Total volume of the tank V_0 (volume of the tetrahedron with vertices 1, 2, 3, 6 and two mutually perpendicular side planes of the tetrahedron):

$$V_0 = \frac{1}{3} S h_0; \quad S = \frac{1}{2} ab; \quad V_0 = \frac{1}{6} abh_0,$$

where a, b is lengths of faces T; h_0 is the calculated height of T according to the information from HPS at vertex 2.

- The volume of the unfilled part of the tank V_{up} with vertices in points 1', 2', 3', 6 is determined by the lengths of the segments of the edges of the unfilled part of the tetrahedron a' and b' cut off by the FM. The sought segments a' and b' are found from the relations for rectangular similar triangles. Through similar triangles formed by vertices 1, 2, 6 and 1', 2', 6' the segment a' is found, and through triangles with vertices 3, 2, 6 and 3', 2', 6' the segment b' is determined:

$$a' = h_{\text{fm}} \frac{b}{h_0}; \quad b' = h_{\text{fm}} \frac{a}{h_0};$$

$$V_{\text{up}} = \frac{1}{6} a'b' \left(h_0 - h_{\text{fm}} \right).$$

- The desired fuel volume is defined as the difference between V_0 and the volume of the unfilled part of the tetrahedron V_{up} :

$$V_x = V_0 - V_{up}$$

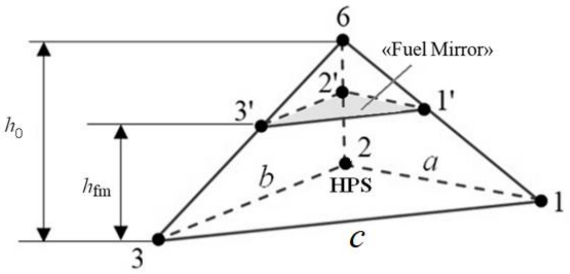


Fig.6.5. Volume of fuel residue for the tetrahedron

6.5.3. Finding the required fuel volume for a tetrahedron of arbitrary shape during horizontal movement of an aircraft

To find the fuel residue in a tetrahedron of arbitrary shape, to calculate the lengths of the segments obtained from the intersection of the fm (fuel mirror) with the edges of the tetrahedron, it is necessary to recalculate the parameters of the vector perpendicular to the FM plane $h_{fm}\{0, h_{fm}, 0\}$ on its inclined edges. Such a problem of computing the volume V_x in segments is solvable, but requires the use of a rather complex algorithm [1].

One of the variants of another solution of the problem of fuel residue determination for an arbitrary tetrahedron can be realized with the transition from volume calculation in segments to volume calculation by coordinates of *fm* intersection with tetrahedron edges.

In general, the equation of the plane, linear with respect to Cartesian rectangular coordinates is [1]:

$$A_x + B_y + C_z + D = 0,$$

where A, B and C not equal to zero simultaneously define the plane.

The equations of three side planes of a tetrahedron of arbitrary shape with one HPSS in one of the vertices of the base, which coincides with the horizontal plane of the instrumental tetrahedron *OENH*, can be represented in the following form:

- plane with vertices 1, 6, 3

$$A_1 x_{ENH} + B_1 y_{ENH} + C_1 z_{ENH} + D_{1ENH} = 0; \quad (3)$$

- plane with vertices 1, 6, 2

$$A_2 x_{ENH} + B_2 y_{ENH} + C_2 z_{ENH} + D_{2ENH} = 0; \tag{4}$$

- plane with vertices 2, 6, 3

$$A_3 x_{ENH} + B_3 y_{ENH} + C_3 z_{ENH} + D_{3ENH} = 0, \tag{5}$$

where

$$D_{1ENH} = Ax_{10ENH} + By_{10ENH} + Cz_{10ENH};$$
$$D_{2ENH} = Ax_{20ENH} + By_{20ENH} + Cz_{20ENH};$$
$$D_{3ENH} = Ax_{30ENH} + By_{30ENH} + Cz_{30ENH}.$$

The parameters of the planes with respect to the *OENH* coordinate system are assumed to be known.

The equation of the FM plane passing through one of its points and perpendicular to the vector **N** {*A,B,C*} can be presented in the following form

$$A(x - x_0) + B(y - y_0) + C(z - z_0) = 0; \tag{6}$$

In the case of parallelism of the FM plane to the *OENH* plane (*A = 0, C = 0*), equation (6) will take the following form:

$$B = (y - y_0),$$

whence at **N** $\{0, h_{fm}, 0\}$

$$D = By_0, \tag{7}$$

$$y = y_0 = h_{fmENH}$$

for all points of the FM.

The *x* and *y* coordinates of the FM for points 1', 2', 3' (Fig.6.5) are found as the intersection of the tetrahedron planes (3) ... (5) with the FM plane (7).

For the coordinates of points 1', 2', 3', respectively, we have three systems of equations and their solution with respect to the three points of intersection of the FM with the tetrahedron :

- for coordinates of point 1'$(x'_{1ENH}, h_{fm}1', z'_{1ENH})$:

$$
\begin{aligned}
&A_1 x_{1ENH} + h_{\mathrm{fm}} + C_1 z_{1ENH} + D_{1ENH} = 0;\\
&D_{1ENH} = Ax_{01ENH} + By_{01ENH} + Cz_{01ENH};\\
&A_2 x_{1ENH} + h_{\mathrm{fm}} + C_2 z_{1ENH} + D_{2ENH} = 0;\\
&D_{2ENH} = Ax_{02ENH} + By_{02ENH} + Cz_{02ENH};\\
&z'_{1ENH} = -\frac{A_2 D_{1ENH} - D_{2ENH} h_{\mathrm{fm}}}{C_{1ENH}};\\
&x'_{1ENH} = \frac{h_{\mathrm{fm}}(C_{2ENH} - C_{1ENH}) + C_2 D_{1ENH} - C_1 D_{2ENH}}{A_2 C_{1ENH} - A_{21} C2_{ENH}}.
\end{aligned} \tag{8}
$$

- for coordinates of point 2'($x'_{2ENH}, h_{fm}2', z'_{2ENH}$):

$$
\begin{aligned}
&A_2 x_{2ENH} + h_{\mathrm{fm}} + C_2 z_{2ENH} + D_{2ENH} = 0;\\
&D_{2ENH} = Ax_{02ENH} + By_{02ENH} + Cz_{02ENH};\\
&A_3 x_{3ENH} + h_{\mathrm{fm}} + C_3 z_{3ENH} + D_{3ENH} = 0;\\
&D_{3ENH} = Ax_{03ENH} + By_{03ENH} + Cz_{03ENH};\\
&z'_{2ENH} = -\frac{A_3 D_{2ENH} - D_{3ENH} h_{\mathrm{fm}}}{C_{2ENH}};\\
&x'_{2ENH} = \frac{h_{\mathrm{fm}}(C_{3ENH} - C_{2ENH}) + C_3 D_{2ENH} - C_2 D_{3ENH}}{A_3 C_{2ENH} - A_2 C_{3ENH}}.
\end{aligned} \tag{9}
$$

- for coordinates of point 3'($x'_{3ENH}, h_{fm}3', z'_{3ENH}$):

$$
\begin{aligned}
&A_1 x_{1ENH} + h_{\mathrm{fm}} + C_1 z_{1ENH} + D_{1ENH} = 0;\\
&D_{1ENH} = Ax_{01ENH} + By_{01ENH} + Cz_{01ENH};\\
&A_3 x_{2ENH} + h_{\mathrm{fm}} + C_3 z_{2ENH} + D_{3ENH} = 0;\\
&D_{3ENH} = Ax_{03ENH} + By_{03ENH} + Cz_{03ENH};\\
&z'_{3ENH} = -\frac{A_3 D_{1ENH} - D_{3ENH} h_{\mathrm{fm}}}{C_{1ENH}};\\
&x'_{3ENH} = \frac{h_{\mathrm{fm}}(C_{3ENH} - C_{1ENH}) + C_3 D_{1ENH} - C_1 D_{3ENH}}{A_3 C_{1ENH} - A_1 C_{3ENH}}.
\end{aligned} \tag{10}
$$

According to the found coordinates of FM and the known coordinates of the tetrahedron vertex $x_{V\ ENH}, y_{V\ ENH}, z_{V\ ENH}$ the volume of the unfilled part of fuel in the tank is determined by the formula [2]:

$$V_{\text{up}} = \frac{1}{6}\begin{vmatrix} x_{V\ ENH} & y_{V\ ENH} & z_{V\ ENH} & 1 \\ x_1^{'} & y_1^{'} & z_1^{'} & 1 \\ x_2^{'} & y_2^{'} & z_2^{'} & 1 \\ x_3^{'} & y_3^{'} & z_3^{'} & 1 \end{vmatrix} \quad (11)$$

6.5.4. Finding the required fuel volume for a tetrahedron of arbitrary shape when maneuvering an aircraft

The volume of the remaining fuel is found as the difference between the a priori known volume of the tetrahedron V_0 and the calculated unfilled part V_{up}.

The obtained solution of the fuel determination problem was considered in the *OENH* coordinate system. At the same time, in the conditions of a fixed base and during the aircraft evolutions, the position of the instrument triangle *OXYZ* will change in accordance with the changes in its angular position relative to the triangle *OENH*, i.e., with the changes in the angles of heading ψ, pitch ϑ, and roll γ of the aircraft. It follows that for finding the coordinates 1', 2', 3' of the FM intersection with the edges of the tetrahedron it is necessary to consider the inclination of the FM plane relative to the movable instrumental trihedral *OXYZ* (Fig.6.6)

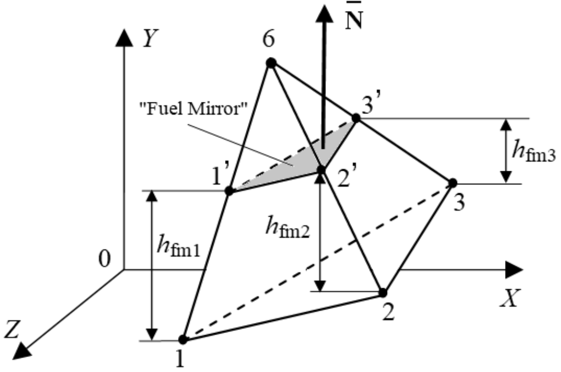


Fig.6.6. Tilt of the "fuel mirror" plane relative to the movable instrumental trihedral

The relationship between the coordinates of the *OENH* triangles in *OXYZ* at the current moment of time can be found through the rectangular matrix of directional cosines

$$\mathbf{B} = L(\psi)L(\vartheta)L(\gamma) \qquad (12)$$

in the form

$$\mathbf{B} = \begin{bmatrix} \cos\psi\cos\vartheta & \begin{matrix}\sin\psi\sin\gamma - \\ -\cos\psi\sin\vartheta\cos\gamma\end{matrix} & \begin{matrix}\sin\psi\cos\gamma + \\ +\sin\psi\cos\vartheta\sin\gamma\end{matrix} \\ \sin\vartheta & \cos\vartheta\cos\gamma & -\cos\vartheta\sin\gamma \\ -\sin\psi\cos\vartheta & \begin{matrix}\cos\psi\sin\gamma + \\ +\sin\psi\sin\vartheta\cos\gamma\end{matrix} & \begin{matrix}\cos\psi\cos\gamma - \\ -\sin\psi\sin\vartheta\sin\gamma\end{matrix} \end{bmatrix}$$

In this case, the coordinates of the tetrahedron planes in the axes of the tetrahedron *OENH* will have the form

$$\begin{bmatrix} x_{V\,ENH} \\ y_{V\,ENH} \\ z_{V\,ENH} \end{bmatrix} = \mathbf{B} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \qquad (13)$$

The angles ψ, ϑ, and γ of the aircraft can be obtained from the inertial navigation system (INS), the heading and vertical system and other meters available on board.

In these cases, the FM plane at points 1',2',3' in the case of its inclination relative to the moving instrument triangle *OXYZ* is defined not by one vector perpendicular to the FM plane $N\{0, h_{\text{fm}}, 0\}$, as it was at zero heading angles ψ, ϑ, and γ of the aircraft, but by three vectors $\{0, h_{\text{fm}}1', 0\}$ as it was at zero heading angles ψ, ϑ and γ of the aircraft, but *three:*

{0, hfm1', 0}, {0, hfm2', 0}, {0, hfm3′, 0}.

Thus, to calculate the heights $h_{fm}1'$, $h_{fm}2'$ and $h_{fm}3'$, it is necessary to have information from three HPS located at the vertices of the base of the tetrahedron (see Fig.6.6).

Thus, to solve the problem of determining the fuel residue in the mobile coordinate system at the current moment of time, it is necessary, in addition to the calculated values of $h_{fm}1'$, $h_{fm}2'$ and $h_{fm}3'$, to have information about the current coordinates of the vertices of the tetrahedron x_i, y_i, z_i and the coefficients of its planes $A_i, B_i, C_i, D_i \quad i=\overline{1K\,4}$ in the coordinate system *OXYZ*. These parameters at the current moment of time can be determined on the basis of the inverse matrix of directional cosines, obtained from the direct square matrix **B** through the known angles ψ, ϑ, γ:

$$\begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} = \mathbf{B}^{-1} \begin{bmatrix} x_{i\,ENH} \\ y_{i\,ENH} \\ z_{i\,ENH} \end{bmatrix} \qquad (14)$$

$$\begin{bmatrix} A_i \\ B_i \\ C_i \end{bmatrix} = \mathbf{B}^{-1} \begin{bmatrix} A_{i\,ENH} \\ B_{i\,ENH} \\ C_{i\,ENH} \end{bmatrix} \qquad (15)$$

$$D_i = A_i x_{i0} + B_i y_{i0} + C_i z_{i0}; \qquad i = \overline{1...3} \qquad (16)$$

Based on relations (14) - (16) and calculated values of heights $h_{fm}1'$, $h_{fm}2'$,$h_{fm}3'$ according to the readings of three FMSs, the system of equations for calculating the coordinates of FM (8) … (10) in the axes of the moving trihedron *OXYZ* is as *follows:*

$$z'_{1XYZ} = -\frac{A_2 D_{1XYZ} - D_{2XYZ} h_{fm}}{C_{1XYZ}};$$

$$x'_{1XYZ} = \frac{h_{fm}(C_{2XYZ} - C_{1XYZ}) + C_2 D_{1XYZ} - C_1 D_{2XYZ}}{A_2 C_{1XYZ} - A_1 C_{2XYZ}}; \qquad (17)$$

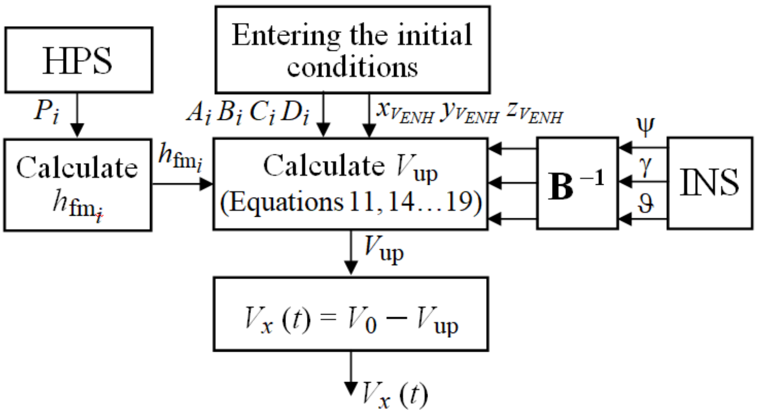
$$z'_{2_{XYZ}} = -\frac{A_3 D_{2XYZ} - D_{3XYZ} h_{\text{fm}}}{C_{2XYZ}};$$

$$x'_{2_{XYZ}} = \frac{h_{\text{fm}}(C_{3XYZ} - C_{2XYZ}) + C_3 D_{2XYZ} - C_2 D_{3XYZ}}{A_3 C_{2XYZ} - A_2 C_{3XYZ}}; \quad (18)$$

$$z'_{3_{XYZ}} = -\frac{A_3 D_{1XYZ} - D_{3XYZ} h_{\text{fm}}}{C_{1XYZ}};$$

$$x'_{3_{XYZ}} = \frac{h_{\text{fm}}(C_{3XYZ} - C_{1XYZ}) + C_3 D_{1XYZ} - C_1 D_{3XYZ}}{A_3 C_{1XYZ} - A_1 C_{3XYZ}}. \quad (19)$$

Based on relations (12) and (14)...(19), the structure of the algorithm for determining the fuel residue at the current moment of time for a tank in the form of an arbitrary tetrahedron for a mobile aircraft can be represented as follows (Fig. 6.7).



6.7. Structure of the algorithm for determining the fuel

6.6. Methodical error of fuel measurement during the flight of the aircraft

When realizing the method of measuring the fuel residue in the tanks of aircraft with the division of tank volumes into tetrahedrons of arbitrary shape, there is a methodological error associated with the oscillations of the fuel surface at the occurrence of aircraft acceleration. For estimation of sensor measurements in the selected time interval of pressure measurement it is supposed to use methods of optimal measurement processing.

At mismatch of planes of tetrahedrons inscribed in the tank volume with real planes of tanks for compensation of methodical error the alignment is required. The alignment procedure can be realized by measuring by means of FMS the readings of current fuel consumption at change of heading angles ψ, ϑ and γ of the aircraft and comparing them with the real readings of fuel residue in the tank. The difference in readings can be considered in flight in the form of corrections coming from the calculator.

6.7. Conclusion FMS based on pressure sensors during the flight of the aircraft

Conclusion : The use of hydrostatic pressure sensors in the system of fuel residue measurement and calculator allows to solve the problem of increasing the accuracy of the aircraft fuel measuring system in all flight modes and to reduce its mass and dimensional characteristics.

CHAPTER 7

PROCESS MODELING

7.1. Changing the position of the fuel in the fuel tank

The aircraft's fuel system during maneuvering performs a complex and multi-functional job, ensuring a continuous and reliable flow of fuel to the engines.

An aircraft usually has several fuel tanks located in the wings and fuselage. When maneuvering, it is important to ensure even weight distribution, so fuel can be pumped between tanks to maintain centering.

The process of fuel flowing from one tank to another can be further visualized using a 3D animation system, as shown below. Fuel leaves tank 1 and flows into tank 2 depending on the change in the acceleration vector. The arrow on the hole indicates the direction of fuel and gas flow through the holes.

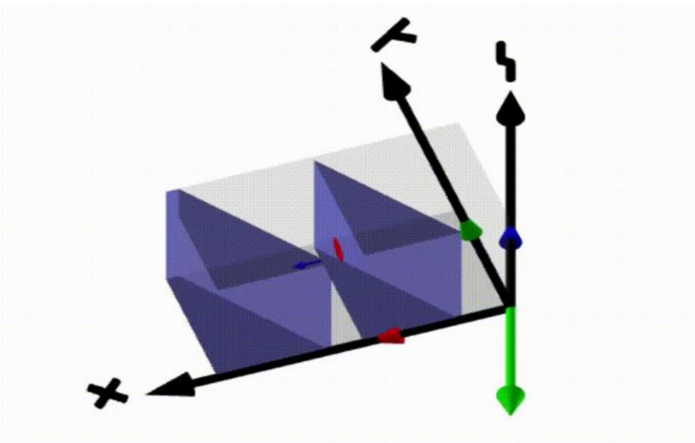


Fig.7.1. 3D visualization of an aircraft fuel system

During maneuvering, for example, when turning or leaning, gravitational forces affect the liquid (fuel) in the tanks. This causes the fuel to shift to one side of the tank. If the aircraft leans, fuel can collect on the lower side of the tank, creating an asymmetric weight distribution.

Fluctuations of fuel in the fuel tank during aircraft maneuvering can be represented in the Matlab :

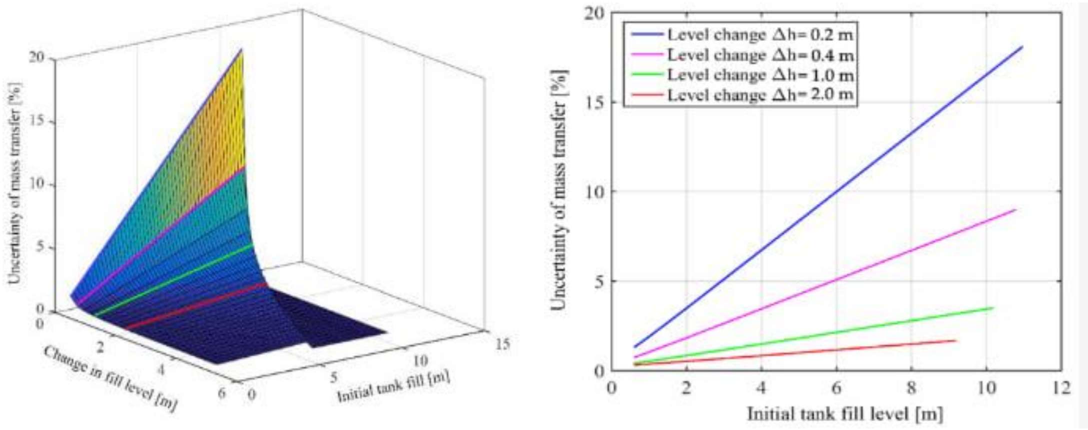


Fig.7.2. Change in fuel position during aircraft maneuvering

7.2. Modeling of the fuel measuring system (FMS) based on pressure sensors

Aircraft fuel-measuring system based on hydrostatic pressure sensors, which makes it possible to determine the fuel residue in the aircraft tanks during its evolutions. The proposed system using hydrostatic pressure sensors and a computer can significantly increase the efficiency of existing fuel metering systems, and can also be used for calibration tests both on the ground and in flight.

As it was said earlier for solve the problem of determining the fuel volume in each of the tanks, it is proposed to divide its space into inscribed volume figures, the fuel volume in which can be calculated separately, and the total fuel volume can be found as the sum of the fuel volumes of the figures inscribed in the tank. In this diplom work, the tetrahedron (T) is considered as an inscribed volume

This aviation fuel measuring system can be developed in the Matlab :

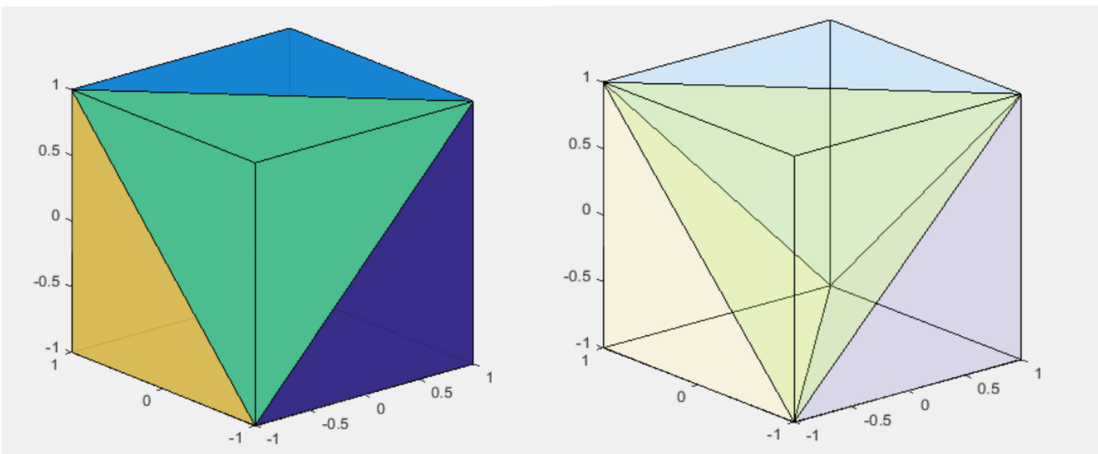


Fig.7.3. The fuel tank is divided into sections (tetrahedrons)

```
% Definition volume in parallelepiped with one pressure sensor,which is located in one of the vertices
% input data
a = 4 ; % Tank (parallelepiped ) width 4 m
b = 3 ; % Tank (parallelepiped ) length 3 m
g = 9.8 ; % Acceleration of gravity - 9,8 m/c^2
P = 820 ; % Fuel density - 820 kg/m^3
p_any = 5000 ; % 5000 pa - 5kPa readings of the HPS, which is located in one of the vertices of the base of the parallelepiped
Hfm = p_any/(P*g); % Fuel level tank
VHfm = a*b*Hfm; % Fuel volume tank
>> VHfm
VHfm =
   7.4664
% Definition volume in a fuel tank with few pressure sensors
% Definition desired volume  T1
VT1_desired = VHfmT1 - VunT1 ; % Desired volume  T1
>> VT1_desired
VT1_desired =
   1.2444
% Definition desired volume  T2
VT2_desired = VHfmT2 - VunT2 ; % Desired volume  T2
>> VT2_desired
VT2_desired =
   0.6222
% Definition desired volume  T3
VT3_desired = VHfmT3 - VunT3 ; % Desired volume  T3
>> VT3_desired
VT3_desired =
```

```
    0.8296
% Definition desired volume  T4
VT4_desired = VHfmT4 - VunT4 ; % Desired volume  T4
>> VT4_desired
VT4_desired =
    1.2444
% The sum of the volumes of the tetrahedrons
>> VTs= VT1_desired+ VT2_desired+VT3_desired+VT4_desired ;
>> VTs
VTs =
    3.9406
>> Vtank=VTs
Vtank =
    3.9406
```

The results of the study showed the difference in volumes between the two methods of determining the volume of fuel using a hydrostatic pressure sensor. The first study, which was carried out with the help of one hydrostatic pressure sensor, showed that the volume in the plane's fuel tank is 7.4664 liters. The next study, which was carried out with the help of several hydrostatic pressure sensors, showed the result of a volume of 3.9406 liters. The study, during which several pressure sensors were used, showed a more accurate result than in the first case.

It is vital to know accurate information about the volume of fuel in the fuel tank of the aircraft during its flight.

CHAPTER 8

INTERESTING FACTS

8.1. Catastrophe ATR 72 near Palermo

Tuninter Flight 1153 of Tuninter Airlines on August 6, 2005 (ATR-72), departed from Bari International Airport in Bari (Italy) and headed for Djerba Airport on the island of Djerba (Tunisia). While flying at cruising altitude, the aircraft's second engine (right) suddenly failed, the pilots initiated a restart when the first engine (left) unexpectedly failed. Because of this, the plane had to make an emergency landing on water, not having reached 20 nautical miles to the nearest airport in Palermo. 16 of the 39 people on board died.

8.2. Chornology of events

During the flight at an altitude of 23,000 feet (~7600 m) the 2nd engine failed, 100 seconds later the 1st engine also failed. After shutting down the engines, the plane began to glide from an altitude of 17,000 feet (~5,700 meters).

The pilots were sure that there was fuel on board the plane, because the fuel gauge showed the presence of 1,800 kg of aviation fuel. Attempts to start the engines were unsuccessful, and Captain Chafik Harby decided to make an emergency water landing.

8.3. Investigation of the incident

Since the captain and co-pilot remained alive, investigators questioned them. Investigators initially believed that the near-simultaneous shutdown of two engines might indicate that the plane was low on fuel. Investigators asked if there were any low fuel signals, to which the pilots replied that there was no low fuel signal, but there was a low fuel pressure signal (later the black boxes would confirm the pilots' words). Investigators began checking the plane's fuel system.

However, the fuel system of the flight 1153 aircraft was functional. Then the investigators paid attention to the quality of the fuel: perhaps the cause of the engine shutdown was dirty fuel. But the examination showed that the fuel is of good quality. At that time, the investigators assumed that the reason for the shutdown of the engines on flight 1153 could be fuel exhaustion.

Meanwhile, the operating company, Tuninter, handed over the plane's maintenance log to investigator Pennett, in which he found an interesting entry. On the eve of the crash, on the evening of August 5, 2005, this plane was also piloted by Captain Harby. After the flight, he made a note about the breakdown of the fuel gauge: not all the numbers are on it. At night, the mechanic replaced the fuel level indicator, as evidenced by the entry in the logbook: "Fuel level indicator installed, type — 2250." Pennetta realized that the cause of the crash could have been a faulty fuel level sensor on another type of aircraft.

The ATR-42 uses a type 2250 fuel gauge and the ATR-72 uses a 2500. Pennetta examined these fuel gauges and realized that they only differed by the type inscription on the housing, but they were shaped the same, so the mechanic could have accidentally installed the wrong type of fuel gauge. But the journal entry could have been a simple mistake, facts were needed.

The ATR-42 uses a type 2250 fuel gauge and the ATR-72 uses a 2500. Pennetta examined these fuel gauges and realized that they only differed by the type inscription on the housing, but they were shaped the same, so the mechanic could have accidentally installed the wrong type of fuel gauge. But the journal entry could have been a simple mistake, facts were needed.

8.4. Experiment with fuel gauges

The investigators conducted an experiment — they refueled the ATR-72 with fuel gauges of the correct and incorrect type. The results shocked everyone: when the tanks were empty, the incorrect fuel gauge read 1,800 kg of fuel - exactly what Captain Harby's fuel gauge was showing.

CONCLUSIONS

In this diploma thesis, the following was carried out: analysis of the aircraft fuel system, analysis of fuel measurement systems, discussion of advantages and disadvantages of all existing systems, research of a fuel measurement system based on a hydrostatic pressure sensor, finding a solution for accurate fuel measurement during the flight of an aircraft, performing simulations given processes.

Based on the results, the following conclusions can be drawn:

- An analysis of existing common aircraft fuel level measurement systems using float and capacitive fuel level sensors shows that these systems measure the fuel level in aircraft tanks with sufficient accuracy only in horizontal flight. During the evolution of aircraft, the measurement of fuel residues in such fuel measurement systems leads to significant methodological errors. In addition, they have a rather complex electromechanical design and significant weight-size characteristics, which collectively affects the general characteristics of the reliability of such vehicles as a whole.
- The results of the study showed the difference in volumes between the two methods of determining the volume of fuel using a hydrostatic pressure sensor. The first study, which was carried out using a single hydrostatic pressure sensor. The following study was conducted using several hydrostatic pressure sensors. The study, during which several pressure sensors were used, showed a more accurate result than in the first case.
- Accurate information on the amount of fuel helps to avoid situations where the aircraft may find itself with insufficient fuel to complete the flight. This is especially important in the event of unforeseen circumstances, such as a deviation from the course due to bad weather conditions or the need to make an emergency landing at an alternate aerodrome.

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APPENDIX A

CALCULATIONS FOR FINDING THE VOLUME OF FUEL IN MATLAB

```
% Construction of model tank
d = [-1 1];
[x,y,z] = meshgrid(d);
X = [x(:) y(:) z(:)]
T = [1 3 4 7;
    4 6 7 8;
    1 5 6 7;
    1 2 4 6;
    1 4 6 7]
tetramesh(T,X);
view(-40,20)
tetramesh(T,X,'FaceAlpha',0.1);
view(-40,20)
% Definition volume in tank with one pressure sensor, which is located in one of the vertices
a = 4 ;
b = 3 ;
g = 9.8 ;
P = 820 ;
p_any = 5000 ;
Hfm = p_any/(P*g);
VHfm = a*b*Hfm
% Definition volume fuel tank with few pressure sensor
%  Definition desired volume  T1
aT1 = 4 ;
bT1 = 3 ; %
p_T1 = 4000 ;
HfmT1 = p_T1/(P*g) ;
VHfmT1 = 1/6*a*b*HfmT1;
aT1_deviv = Hfm * bT1/HfmT1;
bT1_deriv = Hfm * aT1/HfmT1;
VunT1 = 1/6*aT1*bT1*(HfmT1-Hfm);
VT1_desired = VHfmT1 - VunT1 ;
%  Definition desired volume  T2
```

```
aT2 = 3 ; %
bT2 = 2 ; %
p_T2 = 7000 ;
HfmT2 = p_T2/(P*g) ;
VHfmT2 = 1/6*aT2*bT2*HfmT2;
aT2_deviv = Hfm * bT2/HfmT2;
bT2_deriv = Hfm * aT2/HfmT2;
VunT2 = 1/6*aT2*bT2*(HfmT2-Hfm) ;
VT2_desired = VHfmT2 - VunT2 ;
%  Definition desired volume  T3
aT3 = 2 ; %
bT3 = 4 ; %
p_T3 = 15000 ;
HfmT3 = p_T3/(P*g) ;
VHfmT3 = 1/6*aT3*bT3*HfmT3;
aT3_deviv = Hfm * bT3/HfmT3;
bT3_deriv = Hfm * aT3/HfmT3;
VunT3 = 1/6*aT3*bT3*(HfmT3-Hfm) ;
VT3_desired = VHfmT3 - VunT3 ;
%  Definition desired volume  T4
aT4 = 3 ; %
bT4 = 4 ; %
p_T4 = 15000 ;
HfmT4 = p_T4/(P*g) ;
VHfmT4 = 1/6*aT4*bT4*HfmT4;
aT4_deviv = Hfm * bT4/HfmT4;
bT4_deriv = Hfm * aT4/HfmT4;
VunT4 = 1/6*aT4*bT4*(HfmT4-Hfm) ;
VT4_desired = VHfmT4 - VunT4 ;
%Definition full volume in tank with few pressure sensor
VTs= VT1_desired+ VT2_desired+VT3_desired+VT4_desired ;
Vtank=VTs
```