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Fly by Wire Advancements in Aviation over Conventional Flight Control Systems

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Abstract: This report shows the advancement of flight control systems, from the old human controlled mechanical systems to the modern fly by wire systems in use today. It also compares the two systems, and investigates the reasons behind the change. This change is a significant and an extraordinary representation of the advancements made in the avionic industry and of the development of aeronautical technologies. The fly-by wire system represents a large fast forwarding in the industry, from complex mechanically controlled systems, to large hydraulically controlled systems, to computer assisted fly by wire system. The use of fly-by wire systems has significantly reduce the weight of the flight control systems, while increasing the scope to add multiple redundancy flight control systems, which can increase the safety in case of failures in a particular system. Further development in fly-by wire systems comes in the form of advancing from analog to digital computing systems.

I. INTRODUCTION

The control and stability characteristics are two key factors in determining the flying and handling qualities of an aircraft. Stability is the ability of the aircraft to return to its equilibrium state after disturbance without any input from the pilot. And control is the ability to maneuver the aircraft into the required position. These two jobs are primarily handled by the flight control systems. The movement of the aircraft can be classified into three groups according to the axis about which the movement is taking place. Rolling is the motion about longitudinal axis, Yawing is the motion about normal axis and pitch is the motion about lateral axis [1]. The main method of controlling these motions is by using control surface on the outside of the aircraft. These are primarily the ailerons, elevators and the rudder. Ailerons provide control in the longitudinal direction (rolling) and are located at the trailing edge of the wings. Elevators are used to control motion in the lateral axis (pitch) and are located on the trailing edge of the rear wings. Rudder is the large vertical wing which can control motion along the normal axis (yaw). The flight control systems enable the pilot to control these surfaces from the cockpit [1]. The flight control systems used over time can be split into different generations from 1902 when the first aircraft was made and successfully flown by the wright brothers to the present generation and also the research being done on further improvements being done to improve the current systems in use. The inherent advantages of fly-by wire systems and the motives to switch to these systems from conventional systems will become apparent as we go through each generation of control systems, their architecture and their method of operation by the pilot.

II. TYPES OF FLIGHT CONTROL SURFACES

All aircraft flight control systems consist of both primary and secondary flight control systems. The primary systems include the ailerons, elevators and rudder which are essential to the control of the flight and are required to safely control the aircraft safely during flight. The secondary control systems constitute the trim devices, wing flaps, leading edge devices and spoilers. These systems can be used to improve the performance of the flight and also to relieve the pilot of excessive control forces [3]. Here we will briefly discuss each of these systems and their components to provide the reader with a basic understanding of the different components involved. (Some aircraft may contain more components which are specific to that aircraft. Included here are the basic components common to all the aircraft).

A. *Primary Control Surfaces*

Primary control systems consist of the following components:

1) *AILERONS:* Ailerons control roll about the longitudinal axis. They are attached to the outboard trailing edge of each wing. They move in in opposite directions to each other. When the control stick is moved by the pilot to one direction, the ailerons move in opposite directions to each other and the direction they move in depends on the direction of movement of control stick. If it is moved to the left, the left aileron deflects upwards and the right aileron deflects downwards. The corresponding change in camber causes the aircraft to roll to the right [3].

2) *ELEVATORS:* The elevator controls the pitch about the lateral axis. Aft movement of the elevator using the control stick deflects the trailing edge of the elevator surface up. This is known as up-elevator position. This decreases the camber of the elevator and increases the downward aerodynamic force to a level greater than what it experiences during level flight. This causes the nose to rise and tail to dip. Causing the nose to dip and tail to rise will require the control column to be moved forwards [3].
3) *RUDDER:* The rudder controls the yawing motion of the aircraft. This happens about its vertical axis. The rudder is fixed to the vertical stabilizer/fin. When the rudder moves left, the airflow around the vertical stabilizer and creates a sideward lift. This moves the tail to the right and yaws the nose to the left [3].

B. *Secondary Control Surfaces*

Secondary control systems consist of the following components:

1) *FLAPS:* They are the most common high lift devices on an aircraft. These surfaces, attached to the trailing edge of the wing can increase the lift or induce drag for any given situation. They allow for a compromise between high cruising speed and low landing speed as the can be extended when needed and retracted when not needed [3].
2) *SPOILERS*: These are found on some fixed wing aircraft. They disrupt the smooth airflow of the air around the aircraft, inducing drag and reducing lift. They are mostly used on gliders to control rate of descent for smooth landings. On other aircraft, they can also be used for roll control. They can also be used to reduce ground roll after landing [3].
3) *TRIM SYSTEMS:* These systems are used to help relieve the pilot of the need to maintain constant pressure on the flight control systems. They usually consist of flight deck controls and small hinged devices attached to the trailing edge of one or more of the primary flight control surfaces. These trim systems aerodynamically assist movement and position of the control surface they are attached to, thus reducing pilot workload. Some of the different types of trim systems are trim tabs, antiservo tabs, ground adjustable tabs etc. [3].

III. CONVENTIONAL (MECHANICAL) FLIGHT CONTROL SYSTEMS

The components used in this type of control systems are push and pull rods, turnbuckles, torque tube, bell crank, fair leads, etc. These systems use mechanical linkages between the controls for the pilot and the wings of the aircraft. They were primarily used in the early ages of aircraft development. They are relatively lightweight and easy to use. However, they are susceptible to damage from external factors like wind, rain etc. Another added disadvantage is that their size and thus consequently their weight increases with the increase in aircraft size. Furthermore, they are highly dependent on the cables being properly tensioned. Failure to do so can cause loss of control and can cause the aircraft to crash [2].

IV. MECHANICALLY ACTUATED HYDRAULIC FLIGHT CONTROL SYSTEMS

These systems started coming into the picture during the Second World War, where increasing aircraft size meant that the strength of the pilot wasn’t enough to move the control surface through mechanical control systems. This introduced the hydraulic systems which would provide the required power to move the bigger and heavier control surfaces by working on the Pascal principle [1]. This however vastly increased the weight of the aircraft. Another issue was the failure of one or both the types of components involved in this system. If the hydraulics failed, then the pilot would still be able to at least partially control the control surfaces, albeit it would require much more effort from the pilot to do so due to the absence of the required force from the hydraulics. However, if the mechanical component fails, then the pilot would lose complete control of the control surfaces as the only objective of the hydraulic system is to provide the necessary force to move the mechanical system which would in turn move the control system [1] [2]. This paved the way to the fly by wire system.

V. FLY-BY WIRE FLIGHT CONTROL SYSTEMS

When the mechanical linkages are replaced by wires and computers, it is known as fly-by wire system. The computers send signals actuators after determining how much the control surface needs to be moved to satisfy the movement of the control yoke by the pilot. Initially it was an analogue technique whereas in recent years it has been transformed into digital systems with the advancement of computers. This vastly reduces the weight of the aircraft and also increases the safety as the computer can be programmed with multiple fail safe programs. Another advantage of this system is the introduction of the autopilot feature, which reduces the workload of the pilot and can make longer flight routes possible [4]. These systems are however more expensive and complex than the other two control systems discussed previously. Further sections will show how flights used one system after another through the ages.

VI. FIRST GENERATION CONTROL SYSTEMS (1903-1945)

The aviation industry took off with the Wright brothers when they made the first plane in 1903. The planes that followed made use of only pulley and cable systems until the First World War. From here until the Second World War, the planes kept getting bigger and soon the pulley systems were replaced with linkages as the pulley-cable systems could not cope with the increased forces acting upon the control surfaces due to the increased size of the aircraft [1].

1) *System Architecture and Operation:* This design was incredibly simple. It used a system of pulleys and cables from each of the three types of control surfaces. Each of these control surfaces had their on-input controls which the pilot used to obtain the desired motion of the plane. As the aircrafts developed further, aerodynamic balancing was introduced to allow the same amount of loads to be moved by the pilot with less force in the input. The pitch motion was controlled using the stick in the right hand, and the rudder was controlled by moving a stick in the right hand from left to right. The pilot would have to move their hips in the 'hip cradle' to cause the aircraft to roll. It is evident that the above system did not have a lot of safety measure and the planes control was highly dependent on the pilot and their experience. This along with increasing sizes of the control surface and the corresponding increase in loads led to the second generation of control systems being developed [1].

VII. SECOND GENERATION CONTROL SYSTEMS (1945-1960)

While the first-generation systems where used (with updates) well into the beginning of the second world war, nearing the middle of the second world war led to the next big advancement in flight control systems. Hydro mechanical systems were being introduced into the bigger bombers and larger transport aircraft. However, the hydraulics were limited to the wings only, controlling flaps during various stages of the flight. After the war, research and development would really take off and systems for commercial airlines were being developed as well. This meant an increase in aircraft size, payload capacity, and number of passengers that the aircraft could accommodate. This led to the development of aircraft such as the Boeing 707 and 727 [1].

1) *System Architecture and operation:* Mechanical connection such as pulleys, rods and cables are directly connected to the control surfaces and give the pilot direct control to the orientation of the plane. However, this can get tiring over a long flight period. Thus, inherent stability was integrated into aircrafts so that the aircraft could correct its position in case of sudden changes in wind direction or if a gust of wind hits the aircraft. In hydro mechanical systems, as the name suggests, the mechanical components are aided by hydraulics which provide the required force, thus allowing the pilot to decrease the input force. These two systems work hand in hand to control the aircraft. The hydraulic fluid used needs to be as close to incompressible as possible to enable the proper movement of the mechanical linkages. The hydraulic fluid is stored in a reservoir and pumps are operated to transport the fluid to the desired place. When the pilot moves the yoke (manual input), it moves the cables and engages the hydraulic system. This opens the control valve, which allows the pressurized fluid to move the control surface through the slave cylinder. This is used for the movement of the ailerons and the elevators. The rudders also operate in a similar fashion, except the pilot controls it with pedals at the feet [1].
2) *System Drawbacks and Advantages:* Hydraulic systems cause a considerable weight penalty, which mandates an increase in the thrust produced by the engine of the aircraft. The hydraulic systems are also high maintenance, and the fluid requires replacement at frequent intervals of time and is a tedious process. However, these disadvantages are offset by the advantages given by the system. It allows for a significant increase in the size of the aircraft, the payload capacity etc. The assistance also decreased the fatigue levels in the pilots. Hydro-mechanical systems are also more rigid and better aero balanced, thus decreasing the possibility of damage due to winds [1].

VIII. THIRD GENERATION CONTROL SYSTEMS (1960-1970)

The previous generation of aircraft used simple hydro-mechanical systems. However, engineers wanted to develop systems which incorporated hydraulic powered actuators. And as the speed and size of the aircraft kept increasing, mechanical control systems became inadequate, as they couldn't respond sufficiently quickly, leading to more mechanical elements to be replaced by hydraulic systems. This research and development led to the introduction of a new component called irreversible power control cylinders [1].

1) *System Architecture and Operation:* In this new generation of hydro-mechanical systems, there are two main components. A mechanical circuit quite similar to the previous generation mechanical circuit. The pilot moves his controls which moves the mechanical circuit, which then activates the hydraulic actuators. The control system includes the pilots' controls, sensors, and actuators, computer systems along with the hydraulic and mechanical components. The main development in this generation is the introduction of actuators, and the connection of actuators to the control surface directly, getting rid of the mechanical linkages. Hydraulic actuation starts with the pressurization of the fluid.

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This pressurized fuel is then converted into a usable force via the actuator. The actuating cylinder consists of casing, pistons, rods and seals. The casing houses the piston and has ports for the fluid to enter and exit. The seals prevent any leakage. When force and torque (from the pilots' controls) are applied to the actuator (irreversible), the system will give a feedback signal which progressively cancels the input signal till the desired position has been reached. The control valve is integrated into the actuation cylinder. Electric signals from the cockpit cause the control valve to move, allowing fluid to enter or exit the actuator. The term irreversible has been given due to the aerodynamic hinge moment not having any effect on their positions [1].

2) *System Drawbacks and Advantages:* Actuators increased efficiency, decreased response time and lessened chances of failure which was considerable high in mechanical components. However, high forces acting on the cylinder made the structure susceptible to damage and this paved the way to the development of the fly-by wire system that is being used throughout the aviation industry today [1].

IX. FOURTH GENERATION FLIGHT CONTROL SYSTEMS: (1970 – 1994)

Fly-by wire (FBW) system is a control system that almost completely eliminates the need for mechanical and hydraulic components and uses computers and wires to relay information and reciprocate the required motion that the pilot inputs using his controls. This system works completely on signals and electrical feedback and no mechanical information relaying system is involved. This system not only got rid of cumbersome and heavy mechanical and hydraulic components, it decreased the weight of the aircraft, improved stability and made the aircraft more agile and maneuverable [1].

1) *System architecture and operation:* The primary flight control surfaces (aileron, elevator and rudder) are controlled using hydraulic actuators. These actuators are connected to the controls in the cockpit via wires running the entire length of the aircraft. As the pilot moves the yoke or operates the pedals, this input is converted into an electric signal and relayed using the wires to the actuators present in the control surfaces [1].
2) *System drawbacks and advantages:* There is a very significant reduction in weight and increase in stability, agility and is significantly less susceptible to failure as compared to mechanical and hydraulic systems. It also reduces the chances for human error. However, these systems are highly prone to high intensity electro-magnetic radiation, which can disrupt signal transmission and cause failures. Avoiding this requires high amounts of electrical shielding and insulation which can increase costs. Significant hours of testing also need to be done to ensure the system works without any problems [1].

X. CURRENT RESEARCH AND DEVELOPMENT AND FUTURE PROSPECTS IN FLIGHT CONTROL SYSTEMS

As the above sections showed, the flight control systems gradually moved from purely mechanical systems to almost entirely being controlled by electric signals and computers, due to various advantages of the latter over the former. However, the requirements in the aerospace industry are getting ever harder to achieve with the current technology, paving the way for newer and better technologies in the future. Growing ambitions need new technology which not only fulfills the requirements, but is also sustainable and environment friendly. One of the key areas of research in recent times keeping environmental needs in mind is the implementation of fly-by wire systems to control the engine from the cockpit. To this day, mechanical and hydraulic controls are used to control the engine, but introducing fly-by wire systems can decrease weight and increase efficiency as an onboard computer can do the calculations and determine the amount of fuel needed to generate the required thrust, thus saving fuel. However, the current paper deals with only the control systems for control surfaces and not the engine controls. Thus, this section discusses future technological opportunities pertaining to flight control systems for control surfaces only.

A. *Fly-by Light Flight Control System*

Fly-by wire systems have hugely dominated the last generation of aircraft due to the substantial advantages they bought. Parallel to this development, there has been an increase in the use of composites in aircraft design, due to their increased strength and reduced weight. However, these materials do not provide the electrical shielding that the wires require from electromagnetic interference. This mandates the use of shielding, which increases cost and weight. To overcome this drawback. Fly-by light has been introduced, which uses optic cables and signals to relay information from the pilots controls to the flight computer systems to the actuators at the control surface. Fly-by light is effective since it is not affected by EMI and high intensity radiated fields. Fly-by light uses optic fibers and optical sensors. These optic fiber cables are lighter than electrical wires by a big margin. Optic fibers also have large bandwidths, thus facilitating greater data transfer speeds, which is highly required as the ever increasing aircraft speeds demand lower response times.

The way this system operates is highly similar to the fly-by wire system with the only difference being that optical signals are used instead of electrical signals. The pilots input is converted into an optical signal to travel to the in-flight computers where it is converted to an electrical signal and processed. This is then converted to an optical signal again, relayed to the actuators at the control surfaces, where the actuators convert it back to an electrical signal, decode it and move the control system to the required position [1].

Apart from the afore mentioned advantages, fly-by light has several other brilliant advantages over fly-by wire systems. The system is much safer in explosive environments due to electric passivity. It is highly durable while also being incredibly light weight. Extremely thin diameters enable induction into smart materials. However, these systems also have major drawbacks which need to be addressed before they can be inducted into commercial aircraft usage. Since it is a relatively new technology, multiple hours need to still be spent in testing the technology thoroughly. Fibre optic connectors are expensive and not readily available compared to their electric counterparts. These are some of the factors due to which despite the obvious advantage of this system over the current technology, no commercial or military aircraft currently employs this technology [1].

XI. CONCLUSION

The aviation industry has come a long way since the Wright brothers first developed a functioning aircraft. Flight control systems is a technology that has undergone a multitude of changes and development. From the first mechanical circuit to the most recent optic fibre cable circuits, flight control systems is one of the most researched components of an aircraft. This development proved to be crucial for the development of other industries like manufacturing, automobile etc. The newly developed components required new methods of manufacturing, which sparked development in the manufacturing industry. And the automobile industry is always looking to implement technology used in the aerospace industry to create better vehicles. And increasing demands and development will surely encourage engineers to conceive even better technologies which will not only meet the necessities of the future generation, but will also ensure sustainability towards the environment.

XII. RESULT

This report discusses the change and development of flight control systems from the beginning of the aviation industry (1903) to the current technology being used industry wide. Subsequently, the advantages and advancements of the fly-by wire system over conventional control systems is made abundantly clear to the user. The methodology of the paper not only informs the reader of the inherent advantages in newer systems, it also enables them to fully appreciate the development path taken and also the significance of each generation and its influence on the development of the next generation of aircraft. Furthermore, future prospects, their advantages and challenges in realizing those technologies have also been discussed.

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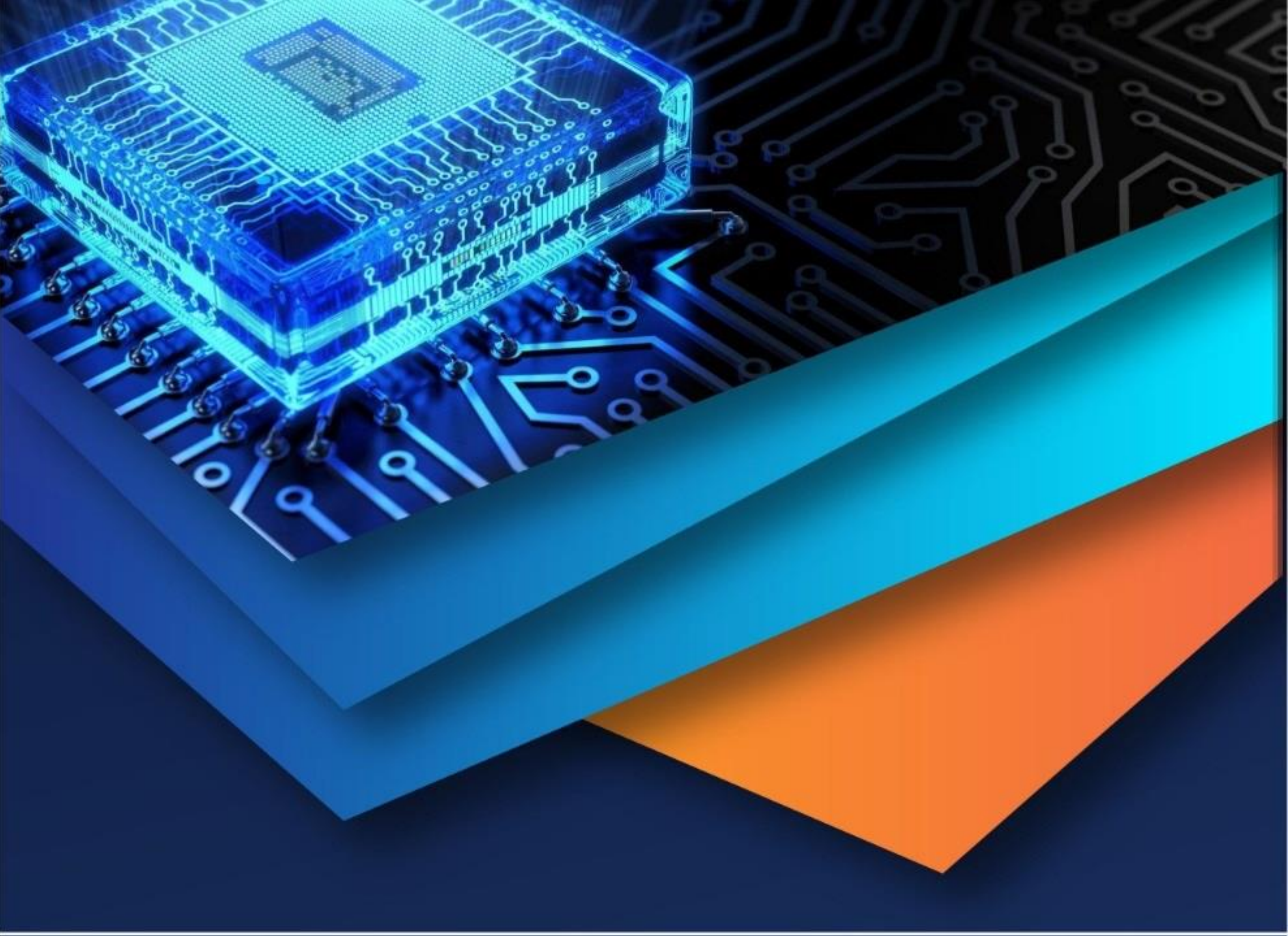

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