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Simulation of the AL-31F Engine Fuel System Using an Electrically Driven Fuel Pump in MATLAB/Simulink

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Abstract- This paper presents a simulation study of the AL-31F engine fuel system using MATLAB/Simulink with the Simscape/SimHydraulics library, focusing on the main fuel supply branch, including the centrifugal pump, the gear pump, and the potential application of an electrically driven fuel pump. The simulation results show that the centrifugal pump exhibits a noticeable variation in flow rate under throttling and changes in rotational speed, whereas the gear pump maintains an almost stable flow rate, is less dependent on outlet pressure, and is not suitable for regulation by throttling alone. On this basis, the use of an electric drive for the fuel pump, especially for the gear pump, is considered a promising approach. It enables fuel flow regulation through pump rotational speed, thereby reducing fuel recirculation, limiting hydraulic losses, and improving the controllability of the fuel system.

Keywords- Fuel system, gas turbine engine, gear pump, centrifugal pump, electrically driven pump.

I. INTRODUCTION

In aviation gas turbine engines, the fuel system plays an important role in ensuring engine starting, acceleration, stable operation, and rapid response under different operating conditions. In two-stream jet engines with an afterburner, fuel is supplied not only to the main combustion chamber and the afterburner, but is also used as a working medium in several hydraulic control mechanisms of the engine.

In conventional fuel systems, the fuel pump is usually mechanically driven from the engine accessory gearbox. This configuration is highly reliable; however, it has a limitation in that the pump rotational speed depends on the engine shaft speed, whereas the actual fuel demand varies with the operating mode and flight conditions. When the pump flow rate exceeds the required demand, throttling or recirculation devices must be used to maintain the required pressure and flow rate. This increases hydraulic losses, fuel heating, and the complexity of the control system.

In the development trend toward "more electric aircraft" and "more electric engines," electrically driven fuel pumps represent a promising approach. This solution allows the pump rotational speed to be decoupled from the engine shaft speed, enabling the fuel flow rate to be regulated directly according to control signals. On this basis, this paper focuses on the simulation of the AL-31F engine fuel system using MATLAB/Simulink, investigates the characteristics of the centrifugal pump and gear pump, and analyzes the applicability of an electrically driven fuel pump in the main fuel supply branch.

II. RESEARCH OBJECT AND BASIS FOR THE APPLICATION OF AN ELECTRICALLY DRIVEN PUMP

2.1. Research Object and Scope

The object of this study is the fuel system of the AL-31F engine, a twin-spool, two-stream jet engine equipped with an afterburner and an adjustable reaction nozzle. In the overall engine structure, the fuel system is responsible for receiving fuel from the aircraft fuel system, pressurizing, filtering, regulating, and distributing it to the consuming components.

The engine fuel system consists of several main subsystems: the low-pressure fuel system, the main fuel system supplying the main combustion chamber, the afterburner fuel system, the drain system, and the emergency fuel dump system. Among these, the low-pressure fuel system performs preliminary fuel pressurization and ensures the required inlet conditions for the downstream pumps. The main fuel system supplies fuel to the main combustion chamber at a flow rate appropriate to the engine operating mode.

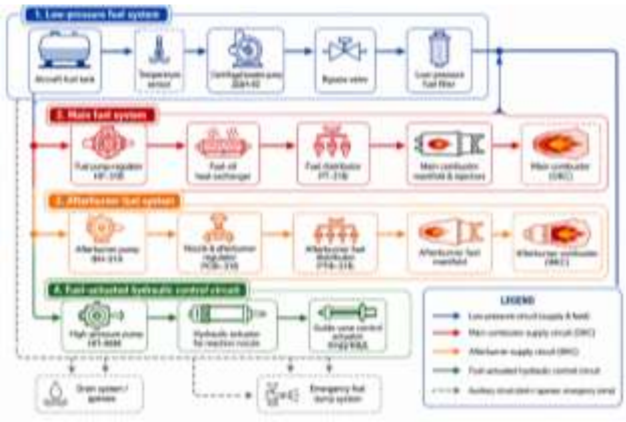


Figure 1. Representative block diagram of the AL-31F engine fuel system

Within the scope of this paper, the study focuses on the main fuel supply branch, which includes basic components such as the fuel tank, the ДЦН-82 centrifugal pump, the fuel filter, the gear pump in the HP-31B pump-regulator unit, pipelines, throttle valve, pressure sensor, and flow rate sensor. This branch is of particular importance for evaluating the capability of fuel flow regulation when the pump drive configuration is changed.

The centrifugal pump in the system performs preliminary pressurization, supplying fuel at a high flow rate and moderate pressure. This type of pump has advantages in terms of weight, high flow capacity, and low sensitivity to impurities in the fuel. However, the outlet pressure of the centrifugal pump strongly depends on its rotational speed; therefore, its operating efficiency decreases under low-flow conditions.

The gear pump in the HP-31B unit belongs to the category of positive-displacement pumps. A characteristic of positive-displacement pumps is that their theoretical flow rate is almost proportional to rotational speed and is only slightly dependent on outlet pressure. This enables the gear pump to generate high pressure, making it suitable for the main fuel supply system. However, because the gear pump maintains an almost constant flow rate at a given rotational speed, it cannot be effectively regulated by outlet throttling as in the case of a centrifugal pump. Excessive throttling may cause a rapid increase in downstream pressure, requiring the use of a safety valve, recirculation valve, or other regulating mechanism.

Based on these characteristics, the application of an electric drive to the gear pump has a clear technical basis. When the pump is driven by a speed-controlled electric motor, the fuel flow rate can be adjusted by varying the pump rotational speed. This approach can reduce dependence on complex hydromechanical regulating mechanisms while improving the accuracy of fuel flow control according to engine demand.

2.2. Basis for the Application of an Electrically Driven Fuel Pump

An electrically driven fuel pump consists of three main components: the pump unit, the electric motor, and the controller. The engine automatic control system determines the required fuel flow rate based on the operating mode, engine control command, rotational speed, pressure, temperature, and other operating parameters. The control signal is then sent to the electric motor controller to adjust the pump rotational speed.

Compared with mechanically driven pumps, electrically driven pumps offer several potential advantages. First, the pump flow rate can be regulated directly according to the actual fuel demand of the engine. Second, fuel recirculation can be reduced, thereby decreasing hydraulic losses and fuel heating. Third, the system can simplify several high-precision hydromechanical control mechanisms. Fourth, since the pump is not completely dependent on the mechanical accessory gearbox, the arrangement of the pump and pipelines can be made more flexible.

However, the application of electrically driven fuel pumps also imposes several technical requirements. The aircraft electrical system must provide sufficient power, appropriate voltage, electromagnetic protection, and high reliability. The electric motor and controller must operate stably under vibration, high-temperature conditions, and strict fire-safety requirements. In addition, the control system must include an appropriate backup strategy to ensure safety in the event of failures in electrical components or power electronics.

III. DEVELOPMENT OF THE SIMULATION MODEL

The simulation model was developed in the MATLAB/Simulink environment using the Simscape/SimHydraulics library. This environment is suitable for modeling hydraulic, mechanical, and electrical systems as multidomain physical models. The components of the fuel system were represented by corresponding functional blocks available in the simulation library.

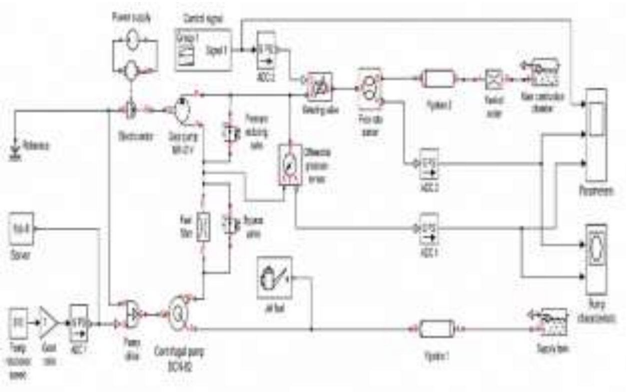


Figure 2. Simulink Model Diagram of the Pressurization Circuit of the Gas Turbine Engine Fuel System

To investigate the pressure–flow characteristics of the pump, a simplified hydraulic model was developed, consisting of a fuel tank, pump, suction and discharge pipelines, a variable-orifice throttle valve, pressure sensor, flow rate sensor, and signal conversion blocks between the Simulink domain and the Simscape physical domain. The pump is driven either by a specified rotational speed source or by an electric motor model. During the simulation, the throttle valve opening is varied over time in order to observe the changes in pump pressure and flow rate.

In the model, fuel is considered the working medium of the system. For the centrifugal pump, the pump characteristic is investigated through changes in pressure and flow rate when the outlet valve area is varied. For the gear pump, the model uses a fixed-displacement pump block with key parameters such as nominal flow rate, inlet pressure, outlet pressure, maximum rotational speed, efficiency, and displacement volume.

To investigate the throttling characteristic, the throttle valve is placed at the pump outlet. During the simulation, the valve flow area is varied over time, from the open position to the gradually closed position. The pressure and flow rate sensors record the system response. The obtained data are displayed on graphs to compare the characteristics of the centrifugal pump and the gear pump.

To investigate the possibility of flow regulation by rotational speed, the model varies the pump shaft speed and records the corresponding outlet flow rate. In the electrically driven pump configuration, the pump rotational speed is considered the control variable and can be varied according to signals from the control system. This provides the basis for evaluating the use of an electric motor in fuel flow control.

In this study, the model is developed with several simplifying assumptions. The fuel is considered nearly incompressible within the investigated range. Mechanical losses, the inertia of some rotating components, and high-frequency pressure oscillations are not fully considered. Internal pump leakage is modeled as a function of the pressure differential. These assumptions are suitable for investigating the general characteristics of the system; however, the model should be further refined if it is to be used for detailed design.

IV. RESULTS AND APPLICABILITY OF THE ELECTRICALLY DRIVEN PUMP

4.1. Results

The simulation results show a clear difference between the operating characteristics of the centrifugal pump and the gear pump in the fuel system.

For the centrifugal pump, as the outlet throttle valve is gradually closed, the fuel flow rate decreases while the pressure downstream of the pump increases. This variation occurs relatively smoothly, reflecting the typical behavior of a dynamic pump. This characteristic indicates that the flow rate of a centrifugal pump can be changed by varying the hydraulic resistance of the pipeline. However, throttling-based regulation is always accompanied by energy losses, since part of the flow energy is dissipated across the valve.

For the gear pump, when the outlet throttle valve is gradually closed, the fuel flow rate decreases only slightly in the initial stage, while the pressure downstream of the pump increases rapidly. This behavior is consistent with the characteristics of a positive-displacement pump. Since the volume of fuel delivered per revolution is nearly fixed, the pump continues to force fuel toward the outlet even as the downstream resistance increases. Without a protective or recirculation mechanism, the pressure may rise to a dangerous level. This result confirms that a gear pump is not suitable for fuel flow regulation by outlet throttling alone.

When the effect of rotational speed is investigated, the results show that the flow rate of both pump types tends to increase as the rotational speed increases. However, for the gear pump, the relationship between flow rate and rotational speed is more clearly linear. This is a favorable characteristic for using an electric motor to control the pump speed. When the rotational speed is precisely controlled, the fuel flow rate can be directly regulated according to the requirements of the engine control system.

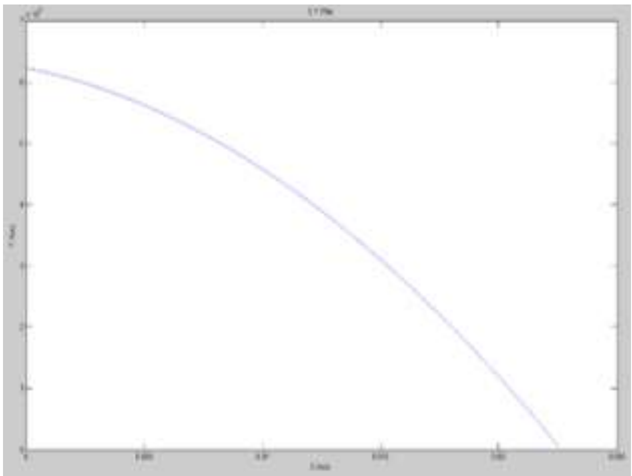


Figure 3. Characteristic of the centrifugal pump expressed by the dependence of pressure on fuel flow rate $P=f(G_T)$

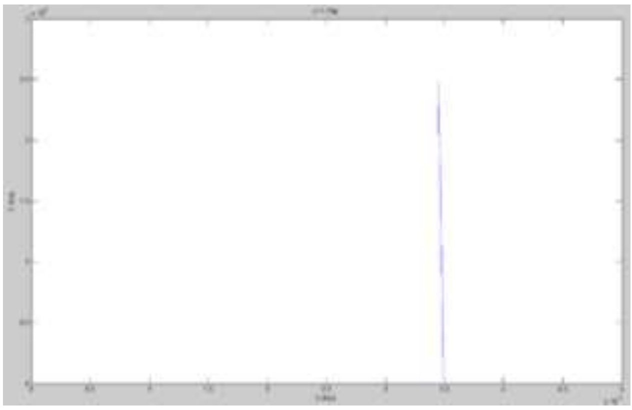


Figure 4. Characteristic of the gear pump expressed by the dependence of pressure on fuel flow rate $P=f(G_T)$

Using a similar method, this block can be used to obtain the relationship between the fuel flow rate through the pump and the rotational speed of the engine rotor. From these characteristics, it can be seen that the delivery capacity of the centrifugal pump changes in direct proportion to the change in impeller rotational speed.

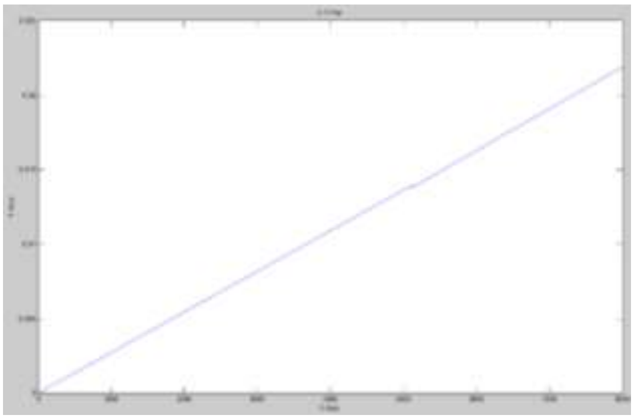


Figure 5. Centrifugal pump flow rate versus high-pressure rotor speed $G_T=f(n_2)$

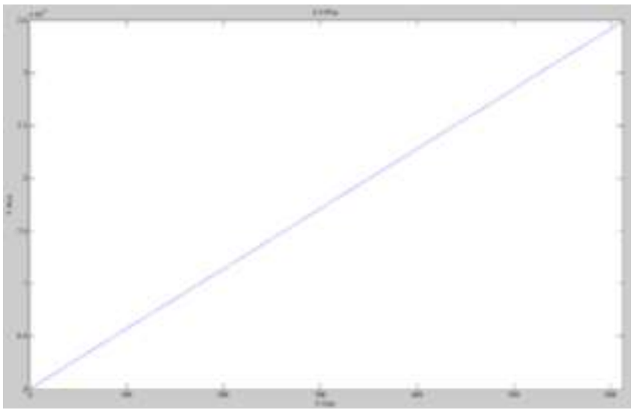
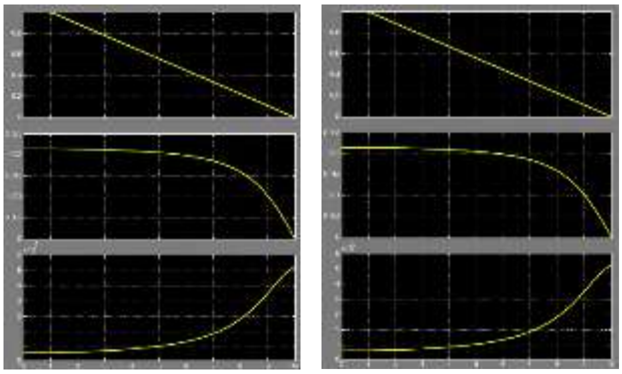


Figure 6. Gear pump flow rate versus high-pressure rotor speed

Then, by using the Scope block, the variation of the main system parameters, such as pressure and flow rate, can be observed on graphs during the simulation process



a) b)

Figure 7. Variation of fuel flow rate and pressure for the centrifugal pump (a) and gear pump (b) during closure of the metering valve

The lower plot shows the time variation of the pressure generated by the pump during operation. The middle plot shows the variation of the fuel flow rate through the pump. The upper plot shows the control signal of the metering valve, which is preset in a separate block.

After analyzing the graphical relationships, the suitability of the original gas turbine engine fuel system during operation can be evaluated. It can therefore be concluded that this model can be used to study and assess the effectiveness of the electric drive unit applied to the high-pressure pump section.

The simulation results indicate that, in a fuel system using a mechanically driven gear pump, hydromechanical regulating mechanisms are required to distribute, throttle, or recirculate the fuel. These mechanisms ensure that the fuel flow rate matches the engine operating mode, but they also increase system complexity, weight, manufacturing precision requirements, and maintenance effort. In contrast, if the gear pump is driven by a speed-controlled electric motor, the pump flow rate can be varied directly by changing the rotational speed, thereby reducing dependence on recirculation valves and complex regulating components.

Another important advantage of the electrically driven pump configuration is its ability to operate in coordination with the engine digital control system. In modern engines, the electronic control system can calculate the optimal fuel flow rate in real time. If the fuel pump is electrically controlled, the control signal can be transmitted directly to the electric motor controller, forming a faster and more flexible control loop compared with a traditional hydromechanical system.

However, the simulation results also show that replacing mechanical drive with electric drive is not merely a change of the pump component. It represents a structural change in the system, involving the power supply, power converter, control algorithm, overpressure protection, signal-loss protection, electric motor cooling, and overall system reliability. Therefore, when studying practical application, hydraulic, electrical, control, and system safety aspects must be evaluated simultaneously.

4.2. Evaluation of the Applicability of the Electrically Driven Pump

Based on the simulation results and the analysis of pump characteristics, it can be seen that the use of an electrically driven fuel pump has a notable technical basis for the fuel system of aviation gas turbine engines.

First, electric drive allows the fuel flow rate to be adjusted according to the actual demand of the engine. For the gear pump, the flow rate is almost proportional to rotational speed; therefore, controlling the pump speed by means of an electric motor is more effective than regulation by throttling. This helps reduce the amount of excess fuel that must be recirculated, decreases hydraulic losses, and limits unnecessary fuel heating in the system.

Second, this configuration can simplify several hydromechanical control units. In a conventional system, maintaining the required flow rate and pressure depends on various regulating valves, recirculation valves, spool valve pairs, and actuating mechanisms. These components require high manufacturing precision and are sensitive to fuel cleanliness. When flow regulation is achieved by controlling pump rotational speed, part of the regulating function can be transferred to the electronic control system.

Third, an electrically driven pump can improve flexibility in system arrangement. Since it does not have to receive mechanical drive directly from the engine accessory gearbox, the pump unit can be arranged more optimally according to space, maintenance, or safety requirements. This is one of the important advantages in the development trend of modern aviation engines.

However, several technical issues must be addressed for practical application. The aircraft electrical power system must have sufficient capacity to supply the pumps and other electrical actuators. The system voltage may need to be increased in order to reduce current and wiring weight. The power controller must have high reliability and be able to withstand harsh operating conditions. In addition, the system must include backup strategies for situations such as power loss, sensor failure, pump seizure, overpressure, or controller failure.

Therefore, the electrically driven fuel pump should not be considered as an isolated replacement component, but should be studied within the overall architecture of a “more electric engine.” In this architecture, mechanical, hydraulic, electrical, and digital control elements are closely integrated to achieve optimum performance in terms of weight, reliability, maintainability, and operating efficiency.

IV. CONCLUSION

This paper has developed and utilized a simulation model of the AL-31F gas turbine engine fuel system in MATLAB/Simulink, focusing on the operating characteristics of the centrifugal pump, the gear pump, and the applicability of an electrically driven fuel pump in the main fuel supply branch.

The simulation results show that the centrifugal pump can change its flow rate when the outlet resistance is varied; however, throttling-based regulation causes energy losses. In contrast, the gear pump maintains an almost stable flow rate, with the flow rate being only slightly dependent on outlet pressure and mainly dependent on rotational speed. Therefore, regulating the gear pump flow rate by outlet throttling is not suitable, since it may cause a rapid pressure increase and overload the system.

From the obtained results, it can be concluded that the use of an electrically driven fuel pump, especially for the gear pump, is a promising approach. This configuration allows the fuel flow rate to be regulated by controlling the pump rotational speed, thereby reducing fuel recirculation, limiting hydraulic losses, simplifying several hydromechanical control elements, and improving integration with the engine digital control system.

In future studies, the model should be further improved by considering the dynamic and nonlinear factors of the system more comprehensively, including fuel compressibility, the inertia of rotating components, pressure oscillations, the dynamic characteristics of the electric motor, the power controller, and the closed-loop control algorithm. In addition, reliability, redundancy, and actual operating conditions in the aviation environment should be further evaluated.

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