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MORE ELECTRIC ENGINE ARCHITECTURE FOR AIRCRAFT ENGINE APPLICATION

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ABSTRACT

This paper describes the system design and evaluation of a noble MEE (More Electric Engine) system. The results show that the proposed MEE system can significantly reduce the fuel burn of engines and CO_2 emissions from aircraft and also improve the safety, reliability and maintainability of engines. The MEE is advanced engine control technology utilizing recent innovations in electrical motors, motor controllers and power electronics. It replaces conventional engine accessories, such as AGB (Accessory Gear Box)-driven pumps, hydraulic actuators with electrical pumps and EMAs (Electro-Mechanical Actuators), which are powered by generators. The first step of the MEE is supposed to be the motor-driven fuel pump system, which can improve engine efficiency by reducing power extraction from the engine and eliminating ACOCs (Air-Cooled Oil Coolers) which worsen fuel efficiency by wasting fan discharge air. The goal of the MEE consists of eliminating the heavy AGB via electrical accessories and an engine-embedded starter/generator. The incorporation of a unique redundant Active-Active control architecture and a fault-tolerant design for the dual motor system successfully achieves a highly reliable and complete one fail operational/two fail safe engine control system.

INTRODUCTION

The aviation industry has been pursuing improved aircraft and aircraft engine efficiency amid global environmental considerations with sustainability in mind. Since reducing fuel burn and CO_2 emissions is a key and urgent issue, many approaches have been researched and developed. Engine manufacturers have striven long and hard to improve each engine component, e.g. compressors, turbines or combustors. However another approach is also necessary for further improved engine efficiency. We focused on a system approach including a control system, fuel system or other engine systems and developed the new MEE. This is an efficient system approach for a future engine with reduced fuel burn and low CO_2 emissions, introducing new electrical technology into the accessory drive and control system. MEA (More Electric Aircraft) architecture, including an electrical ECS (Environmental Control System) or starter/generator, has been incorporated into recent commercial aircraft [1, 2] and also uses advanced electrical technology. The purpose of this paper is to show the benefits, system concepts and simulation study of the proposed MEE.

NOMENCLATURE

AGB: Accessory Gear Box
ACOC: Air-Cooled Oil Cooler
EMA: Electro-Mechanical Actuator
FADEC: Full Authority Digital Electronic Control
FCOC: Fuel Cooler Oil Cooler
FMU: Fuel Management Unit
IFSD: In-Flight Shutdown
OSL: Overspeed Limiter
OSV: Overspeed Valve
SFC: Specific Fuel Consumption
GCU: Generator Control Unit
SOV: Shutoff Valve
MEA: More Electric Aircraft
MPV: Minimum Pressurizing Valve

DEVELOPMENT STEP OF THE MEE

In a conventional engine system, engine accessories are driven by the AGB as shown in Fig. 1, with typical examples including the fuel pump, oil pump and alternator. Actuators for the engine variable geometry are hydraulic actuators and the FMU (Fuel Management Unit), which meters fuel flow supplied to the engine, is a hydro-mechanical component with various precise valves. One of the key concepts of the proposed MEE system is to change the power source for accessories from the AGB to the electrical motor [3, 4]. The MEE development is divided into the following three steps as shown in Fig. 2:

(a) STEP 1: Electrical motor-driven fuel pump system
(b) STEP 2: Starter/generator and power management
(c) STEP 3: Engine-embedded starter/generator

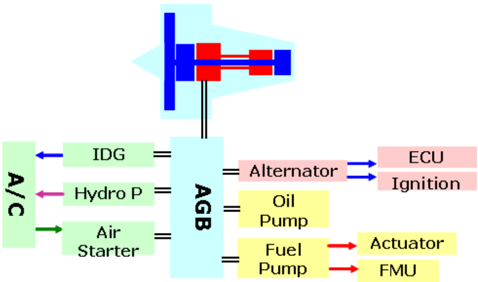
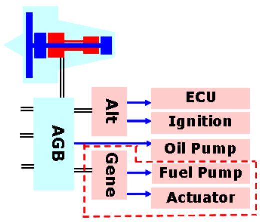
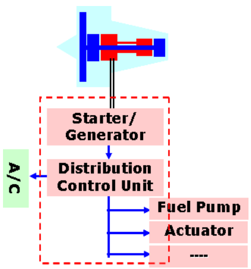


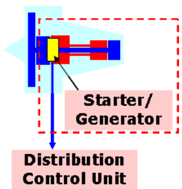
Figure 1 Conventional AGB-driven accessories



<MEE STEP 1>
Electrical motor-driven fuel pump system



<MEE STEP 2>
Starter/generator and power management



<MEE STEP 3>
Engine-embedded starter/generator

Figure 2 MEE system development steps

(a) STEP 1: Electrical motor-driven fuel pump system

STEP 1 improves the fuel system efficiency by replacing the conventional AGB-driven fuel pump with an electrical fuel pump. The FMU is eliminated since the fuel metering function is performed by the fuel pump speed control. Hydraulic actuators are replaced with EMAs. STEP 1 pursues key technology for the electrical motor-driven system and reduction of the fuel burn.

(b) STEP 2: Starter/generator and power management

STEP 2 eliminates the AGB and replaces both fuel and oil pumps with electrical pumps, while the engine air starter is replaced with a starter/generator. Since the latter generates electrical power for both engine and aircraft accessories, the AGB is no longer needed. Because the AGB is one of the heaviest external engine components, its elimination reduces the engine weight, and hence the engine fuel burn. Since electrical power management is important for STEP 2, a distribution control unit will be necessary.

(c) STEP 3: Engine-embedded starter/generator

STEP 3 involves embedding the starter/generator inside the engine to decrease the nacelle front area. No AGB or starter/generator is externally attached to the engine. The nacelle front area will be decreased, improving the aircraft efficiency, because its drag is reduced [5].

ADVANTAGES OF THE MEE

There are several benefits when the conventional AGB-driven accessory system is replaced by the MEE system. These can be divided into the following three categories:

(a) Reduced fuel burn and CO_2 emissions
(b) Improved engine safety and reliability
(c) Improved maintainability

The proposed MEE system emphasizes the advantages in categories (a) and (b) by introducing unique technical approaches. The benefits and concepts accomplished by the proposed MEE system are summarized in Table 1.

Benefits by the proposed MEE system		Concepts of the proposed MEE System
(a) Reduced fuel burn and CO_2 emissions	SFC reduction	- Improvement of fuel pump system efficiency - Improvement of engine oil heat management
	Engine weight reduction	- Elimination of AGB - Small and light electrical components with high voltage electrical system
(b) Improved engine safety and reliability	One fail operational/ two fail safe	- Unique Active-Active control of redundant motor system
	Prevention of engine fire	- Reduction of fuel/oil tubes - Reduction of fire vulnerable seals
	Reduction of engine overspeed failure	- Overspeed prevention by fuel pump motor power-off
	Reduction of IFSDR	- Elimination of FMU and contamination sensitive valves
(c) Improved maintain -ability	Replacement time of LRU	- Reduction of hydraulic interface
	Environmental consideration	- Reduction of drainage of hydraulic fluid

Table 1 Benefits and concepts of the proposed MEE system

REDUCED FUEL BURN BY THE MEE

Reducing the fuel burn, which will then reduce CO_2 emissions, is the largest and key benefit accomplished by the MEE system. In MEE STEP 1, the electrical fuel pump system can improve the engine efficiency by:

(a) Improving the fuel pump system efficiency, eliminating the fuel bypass circuit

(b) Improving the engine oil heat management, eliminating the ACOC

(a) Improvement of the fuel pump system efficiency

Currently, most aircraft engines use a fixed displacement fuel pump such as a gear pump or vane pump. The speed of the fuel pump driven by the AGB is proportional to the core engine speed. The pump must be dimensioned to ensure sufficient capability of the fuel supply at lower engine speeds, such as engine start or ground idling. As a result, the pump provides a far higher flow than the engine burn flow, especially at higher engine speed at higher altitude. The fuel system must bypass the excess fuel flow to return to the fuel pump inlet and the excess fuel flow is sometimes several times larger than the engine burn flow. The recirculation of the excess flow results in fuel system inefficiency as well as a rise in fuel temperature.

The MEE system can improve fuel system efficiency by eliminating the bypass circuit for the excess flow. The electrical fuel pump in the MEE is a fixed displacement pump, which discharges fuel flow in proportion to the pump speed. The pump speed is controlled by the electrical motor so that the pump discharges the exact fuel flow demanded by the FADEC (Full Authority Digital Electronic Control). The motor-driven fuel pump consists of the pump itself, the motor controller and inverter. During engine operation, the FADEC computes the fuel flow required by the engine and transmits the fuel flow demand to the motor controller, which then manages the motor speed. In a conventional fuel system, an AGB-driven fuel pump and FMU are used to deliver the fuel required by the FADEC to the engine combustor. The FMU contains a metering valve, which varies the metering port area corresponding to the fuel flow demand from the FADEC, a bypass valve which bypasses excess fuel into the pump inlet and a pressure regulating valve, which maintains a constant pressure difference upstream and downstream of the metering valve. The MEE system can eliminate the FMU, which is a highly complicated hydro-mechanical unit.

A generator driven by the AGB supplies electrical power for the motor-driven fuel pump. Comparing the conventional AGB-driven and motor-driven fuel pumps in terms of respective power extraction from the engine, the latter certainly takes less power than the AGB-driven pump under an equivalent operational condition, because it eliminates the inefficient bypass flow circuit.

(b) Improvement of engine oil heat management

Another benefit of the MEE is improved engine oil heat management. Heat management of both oil and fuel has become a serious issue for recent high bypass turbofan engines [6]. These have significantly reduced engine burn flow compared to that of low bypass turbofan engines. Engine oil absorbs the heat generated at engine bearings, seals, AGB and various accessories. Recent turbofan engine systems utilize both FCOCs (Fuel Cooled Oil Coolers) and ACOCs to cool the engine oil. Since the oil cooling capability of an FCOC, which uses burn fuel flow, is insufficient for modern high bypass turbofan engines, an ACOC is used to augment the FCOC. The ACOC extracts precious fan discharge air, which is then exhausted outside the engine, thus worsening engine efficiency. Reduced burn fuel flow at a recent higher bypass ratio turbofan engine compounds the situation.

The MEE electrical fuel pump minimizes the fuel temperature rise in the fuel system due to the lack of recirculation flow, meaning the FCOC can remove considerable heat from the engine oil using cooler fuel as a coolant. For higher bypass ratio engines with the conventional AGB-driven fuel pump systems, the fuel temperature may increase by a maximum of around 100K from the engine inlet to the FMU outlet. In contrast, the fuel temperature rise of the MEE system is expected to be limited to one tenth of the same. This improved FCOC cooling capability allows the ACOC to be eliminated, significantly improving the engine efficiency.

A simplified schematic diagram of the MEE STEP 1 is shown in Fig. 3.

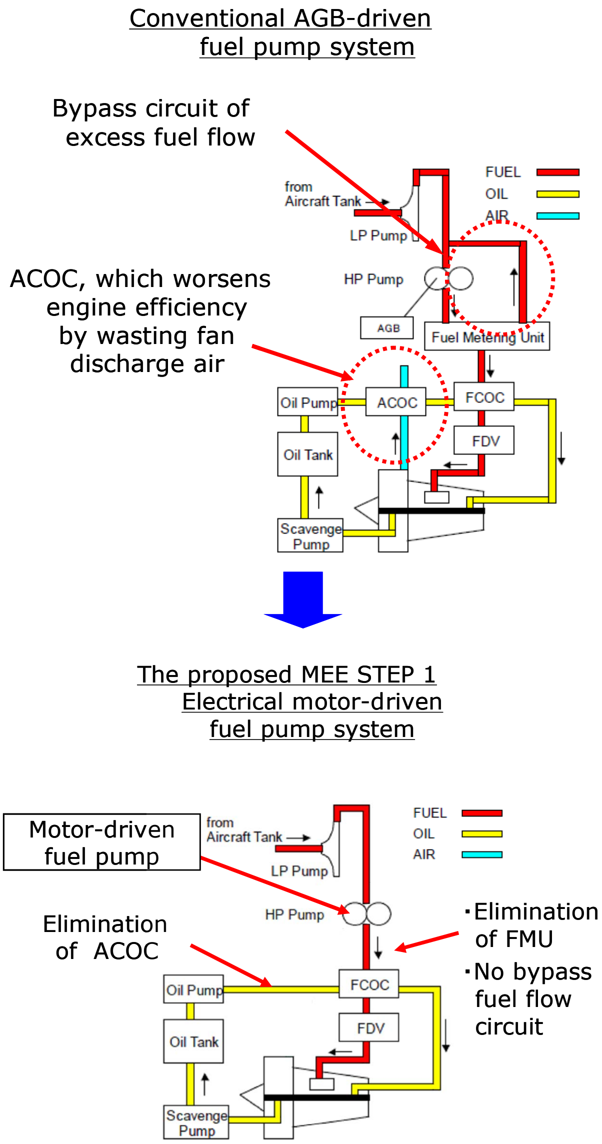


Figure 3 A highly efficient electrical fuel pump system

Reduction of the fuel burn was evaluated on a small turbofan engine. An SFC (Specific Fuel Consumption) calculation was conducted using an engine performance calculation program, where power extraction from the engine by accessories and the fan air extraction by the ACOC were taken into consideration.

As shown in Fig. 4, the MEE electrical fuel pump system extracts around half the power from the engine compared with conventional AGB-driven systems. As a result, the MEE system improves SFC by about 0.4% under cruise conditions. Elimination of the fan discharge air extraction by the ACOC resulted in an improvement of about 0.6% of SFC under cruise conditions. Total SFC improvement was presumed to be about 1.0% under cruise conditions as shown in Fig. 5, while the reduction of the total fuel consumption during an estimated aircraft mission was also calculated at about 1%.

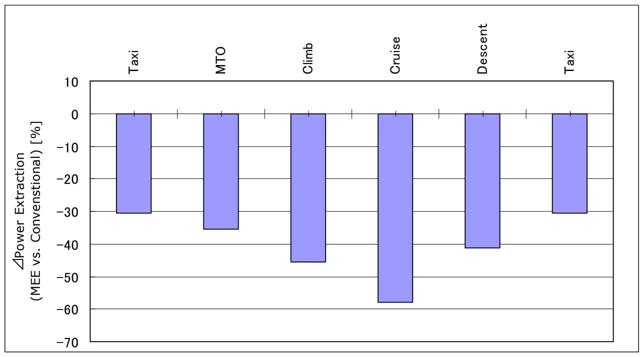


Figure 4 Reduction of power extraction from the engine

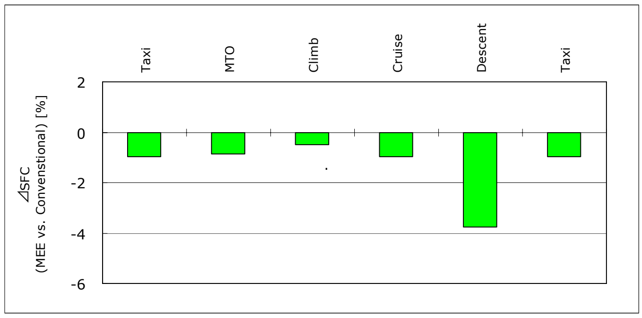


Figure 5 SFC reduction accomplished by the MEE STEP 1

To improve the engine oil heat management, other approaches such as an AGB-driven variable displacement fuel vane pump or a surface type ACOC have also been developed. However, although they improve engine efficiency, they also exert several impacts on the engine or component mechanical design. The surface-type ACOC should have a large mounting area inside the fan case for heat exchange. The variable displacement vane pump requires a complicated mechanism, including servo valves and pistons to vary the pump displacement. The MEE electrical fuel pump system, which consists of an electrical motor and a fixed displacement gear pump, would be a simpler and more durable approach than the others to improve engine efficiency.

In addition the MEE components have greater flexibility in terms of installation on the engine because the components can be apart from the AGB or fuel pressure source. The MEE STEP 1 will improve engine efficiency with minimum impact on the engine system or mechanical design, which certainly represents a major advantage of the MEE system over other approaches.

REDUCED ENGINE WEIGHT BY THE MEE

Another benefit of the MEE is the reduction of engine weight. The MEE STEPS 2 and 3, which eliminate the heavy AGB as shown in Fig. 2, will significantly contribute to engine weight reduction. The reduced weight also reduces the fuel burn and decreases the fleet operational cost by increasing the amount of fuel in the aircraft tank at takeoff.

To emphasize the engine weight reduction, the proposed MEE adapts a higher voltage electrical system than conventional aircraft/engine electrical systems. Most conventional aircraft use a 115V DC bus for the electrical power management. Recent MEA, for example the Boeing 787, utilizes a higher voltage 230V AC bus. The higher voltage means electrical circuits and components work at a lower current, resulting in a reduced electrical wire diameter and volume of electrical components. The voltage should be carefully determined, but a level equivalent to the recent MEA, a minimum of 230V AC, will be incorporated into the proposed MEE system.

We conducted a comparison of the engine weight between a conventional AGB-driven fuel system and an MEE electrical fuel pump system for the small engine. For the MEE STEP 1, the elimination of ACOC and FMU, and a smaller fuel pump and fuel filter reduce the engine weight. Conversely, the added generator, electrical motors, motor controllers and inverters increase the engine weight. As shown in Table 2, current estimation indicates a slight increase of engine weight. There are some ideas for minimizing weight increment, which are not taken into account in the current weight estimation, such as using commercial electronic parts and/or further increasing the voltage.

Components	Contents	Reduction	Increment
Fuel pump system	Electrical motor-driven fuel pump system		
	-Addition of electrical motor unit		+14kg
	-Reduction of pump size	-7kg	
	-Reduction of filter size	-5kg	
	-Elimination of FMU	-11kg	
	-Elimination of ACOC & duct	-13kg	
Actuator	Addition of electro-mechanical unit and devices		+8kg
Generator	Addition as power source for pump and actuator		+21kg
Total		-36kg	+43kg
		+7kg	

Table 2 Comparison of engine weight for the MEE STEP 1

The evaluation results of the fuel burn and the engine weight reduction are only shown for the small turbofan engine. However for large engines as well as small engines, the introduction of the MEE system is expected to provide a similar advantage in terms of reduced fuel burn, because the power extraction from the engine is simultaneously minimized. Large engines require large motor output torque to drive the fuel pump or actuator. The latest improvements in power electronics provide sufficient design solutions for the motor and relevant components, making it possible to obtain such high power with the size of components available. In considering the large engine application, minimizing the weight and volume and optimizing the system should be discussed. The use of a large output torque motor enlarges its weight and volume due to the need to dissipate the heat generated. When designing motor systems, a trade-off among the weight, volume and heat dissipation is necessary considering the installation envelope and the weight impact on the engine. To make the MEE system and components feasible for the large engine, many design approaches adopting higher voltages, higher motor speeds and multiple pump systems should be considered.

IMPROVED ENGINE SAFETY AND RELIABILITY

If we introduce the new MEE system instead of a conventional system, consideration of engine safety and reliability is crucial. The proposed MEE achieves reliability superior to conventional systems by introducing a unique redundant control system architecture.

The proposed MEE system successfully incorporates the following reliability and safety concepts into the engine:

(a) One fail operational; No thrust change of the engine with single failure in the motor-driven fuel pump system
(b) Two fail safe; Continuous operation of the engine with dual failures in the motor-driven fuel pump system
(c) System safety; Reduction of aircraft catastrophic failure rate induced by the engine

(a) One fail operational system accomplished by the MEE

No thrust change of an engine with single failure will be accomplished by the unique Active-Active control of the redundant motor system. In most aircraft or aerospace applications, electrical actuators or components adapt Active-Standby control. The Active-Standby redundant motor system consists of dual motors and dual motor controllers/inverters. An active or stand-by channel is assigned for one of the dual motor systems. When a single failure in the active channel is detected, control authority of the motor system is switched to the stand-by channel. This is the standard control method of the dual electrical system, but if it is applied to the MEE electrical fuel pump system, the following problem occurs. The time lag for switching from one channel to the other means the motor speed rapidly decreases, which may result in interruption of the fuel flow and the engine flaming out or a sudden thrust change. The MEE system should avoid this critical situation with flight safety in mind. To do so, the Active-Active redundant control is used in the proposed MEE system. Single open failure in windings in any portion of one of the motor systems does not require channel switching and the motor current is automatically substituted. Since no mechanical or electrical switching mechanism is required, the Active-Active redundant control system is highly reliable, durable and simple.

Figure 6 shows a block diagram of the redundant motor system for the fuel pump. A three phase brushless motor, as shown in Fig. 7, is used. The motor consists of two sets of windings of an "A" and "B" system respectively, with each set connected to a controller and inverter respectively. A neutral line is connected between both neutral points of a star connection in the "A" and "B" systems. If a short-circuit failure occurs at one of the phases, for example the U-phase in the inverter of the "A" system, the short circuit electrical current flows through the neutral line and not to the other phases, namely the V- and W-phases of the "A" system. This means a single failure in the U-phase does not impact on other phases. At the same time, the input current in the U-phase of the "B" system is adjusted automatically. In the three phase/dual winding motor system, current sensors detect the electric current flowing through each phase (U-, V-, and W-phases), and the detected current signals are fed back to the controller via an interface circuit. The feedback current signals in the "A" and "B" systems are combined in the interface circuit, whereupon the mean value of the feedback current is calculated and the difference between the mean value and current command value is input to the controller. Subsequently, the input currents for the "A" and "B" systems are automatically adjusted to maintain a mean value corresponding to the command. If a single failure occurs in the "A" system, i.e. its feedback current becomes zero, the input current for the "B" system is automatically doubled and the mean value remains the same. The motor can generate the same torque for the pump, which therefore continues to work at the same speed and maintains a constant discharge flow. The MEE electrical fuel pump system utilizing this Active-Active control architecture accomplishes the one fail operational system without any speed or thrust change of the engine.

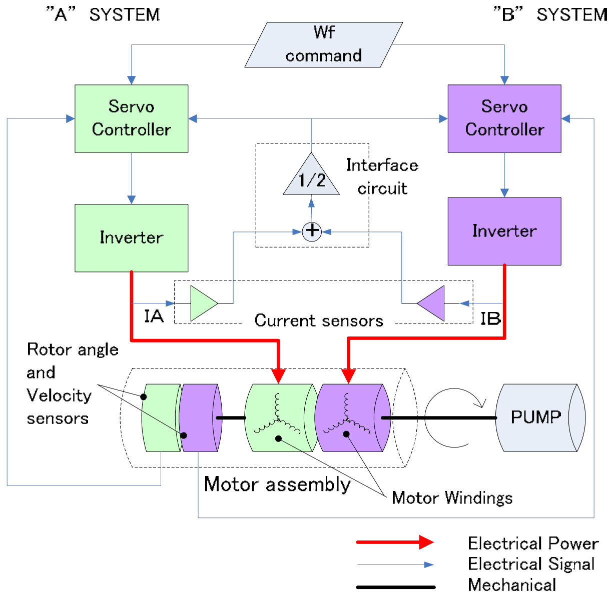


Figure 6 Block diagram of the redundant motor system

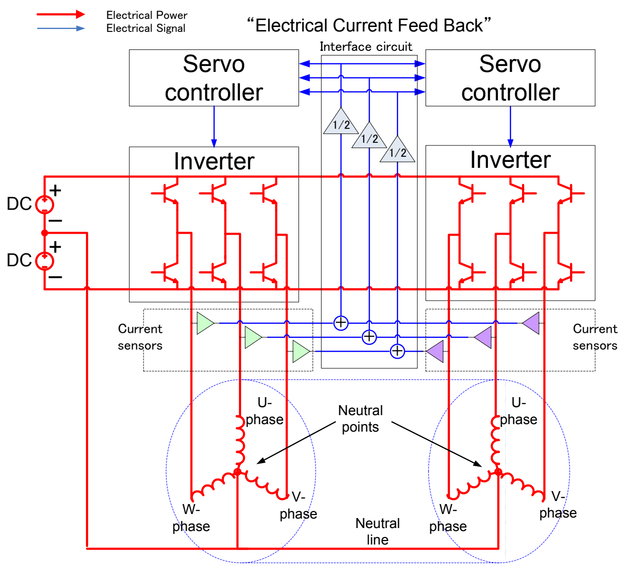


Figure 7 Active- Active control for three phase/dual motor

(b) Two fail safe system accomplished by the MEE

Continuous operation of the engine with dual failures in the motor system is certainly an advantage in terms of engine safety and reliability. A unique fault-tolerant design for the redundant three phase brushless motor system, which enables the motor-driven fuel pump to continue supplying a certain amount of fuel and thus prevents the engine shutdown due to dual failures, will be incorporated into the proposed MEE system. The Active-Active control architecture described above (a) enables the motor system to continue working when initial failure occurs in one of the phases and second failure occurs in another, i.e. the motor operation will be maintained, even in the event of dual failures. However, if dual failures occur in the same phase of both "A" and "B" systems, the motor rotation will halt or become instable. To avoid this, an additional fault-tolerant concept must be introduced. Several solutions are available, such as a triple rather than double redundant system or five rather than three phase motor windings. Further investigation is currently underway in order to accomplish the two fail safe condition with a simple and compact system and component design.

(c) System safety accomplished by the MEE

Although the fatal accident rate involving aircraft has significantly decreased in recent decades, further improvement is still necessary. Engine failures which may cause catastrophic aircraft failure are as follows: engine fire, engine overspeed and engine IFSD (In-Flight Shut Down). The proposed MEE system can reduce such engine failures.

(1) Prevention of engine fire

The conventional AGB-driven accessory system has many components filled with flammable fluid and tubes and hoses connecting them. The MEE system does not require fuel lines other than the supply line of the burn flow to the combustor, and eliminates FMU, the bypass line from the FMU to the fuel pump inlet and the actuator supply/return lines. In addition, non-metallic seals, which are vulnerable to fire, are also significantly reduced in the MEE system.

(2) Reducing the engine overspeed failure

The engine overspeed prevention system is also unique to the MEE system. A FADEC system should have an overspeed prevention mechanism isolated from the normal engine control. A typical OSL (Overspeed Limiter) system, used in a dual channel FADEC system, consists of an electrical OSL and hydraulic OSV (Overspeed Valve) as shown in Fig. 8. If the engine speed sensors detect engine overspeed, which may be due to either engine mechanism or control system failures, the OSL commands the OSV to shut or reduce the burn flow. The MEE system can then introduce an additional method to shutoff the burn fuel flow. Powering off the motor can simply stop the fuel pump and shutoff the fuel flow to the combustor. The OSL system becomes redundant as shown in Fig. 9, by employing both fuel flow shutoff methods of OSV and motor power-off, meaning the occurrence of engine overspeed failure rate will be significantly reduced.

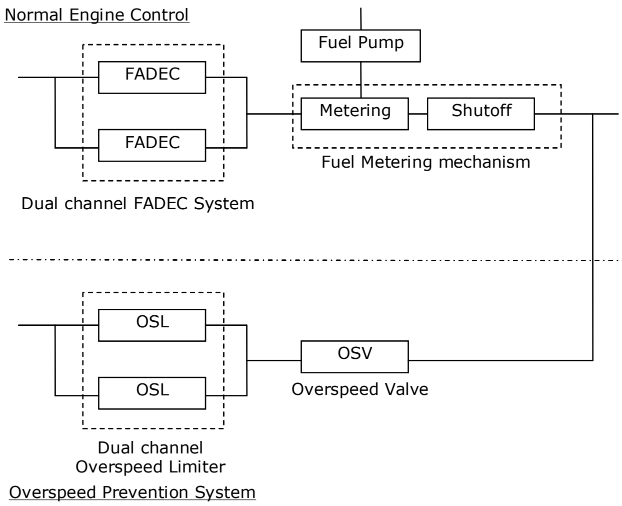


Figure 8 Conventional engine control and OSL system

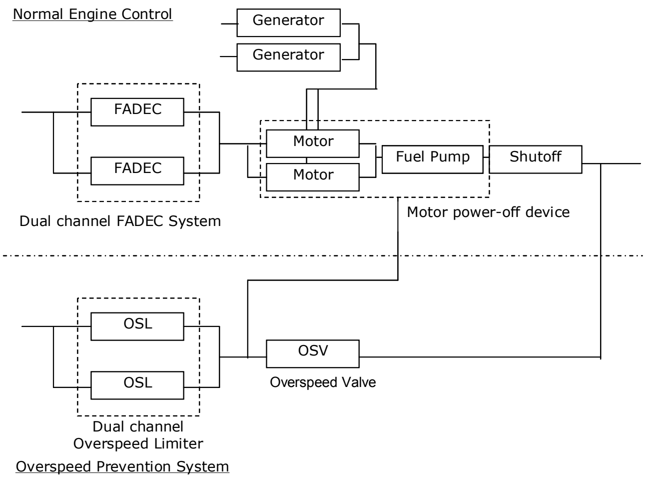


Figure 9 The MEE engine control and OSL system

(3) Reducing the engine IFSDR

It is relatively easy for the electrical system to adopt a system approach such as multiple redundant system or a fault-tolerant concept, to reduce the occurrence of critical failures. The MEE system strives to reduce the engine IFSDR by constructing a one fail operational/two fail safe system with avoidance of the engine IFSD upon the occurrence of dual failures in the fuel pump motor. In addition, the MEE electrical fuel pump eliminates the FMU. The metering, bypass and pressure-regulating valves in the conventional FMU require very tight manufacturing tolerances and are vulnerable to contamination. Their failure rate is thus relatively higher than the other parts in the fuel system and is the main factor governing IFSDR caused by the conventional control system. Although the recent design and manufacturing capability of such valves have enabled the FMU to achieve better reliability than ever, incidents of valve malfunction remain due to contamination or extended operation. The MEE pursues lower engine IFSDR by a system approach using the proposed Active-Active control architecture and a fault-tolerant system design, as well as a component approach to eliminate vulnerable parts in the hydraulic system.

THE MEE SYSTEM CONFIGURATION

The typical MEE STEP 1 electrical fuel pump system configuration is shown in Fig. 10. This consists of a motor-driven fuel pump, EMA, generator, GCU (Generator Control Unit), SOV (Shutoff Valve), OSV and MPV (Minimum Pressurizing Valve). The FADEC, OSL and fuel nozzle are considered similar to the conventional system.

The motor-driven fuel pump includes a motor controller and inverter. The engine burn flow demand is input from the FADEC to the motor controller, where it is converted to motor speed. Feedback control of the motor speed is implemented within the motor-driven fuel pump and fuel flow roughly proportional to the pump speed is supplied to the engine. The actuator stroke demand input from the FADEC to the actuator controller is converted to the motor speed and feedback control of the latter is conducted to accommodate the stroke demand.

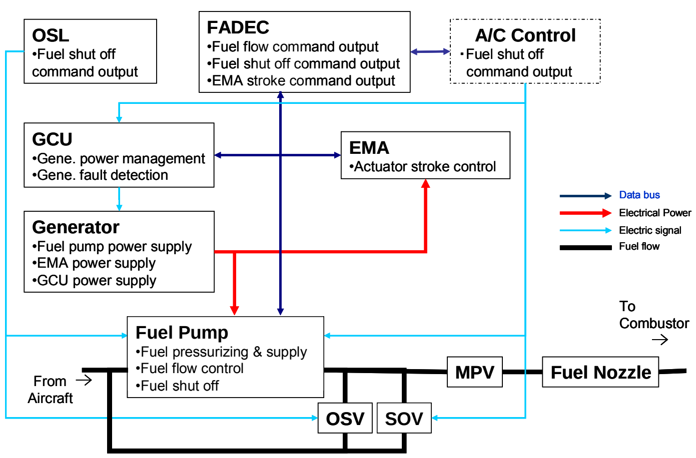


Figure 10 Typical MEE STEP 1 configuration

The generator is the electrical power source for the pump and EMA. The GCU performs power management of the generator, including start/stop control of the power supply from the generator to components and fault detection of the generator. The FADEC has the authority to start/stop the fuel flow and the actuator stroke control. A data bus is used for communication between the FADEC, GCU and other components to ensure wide communication capability.

The FMU and contamination sensitive valves are eliminated in the MEE system. The fuel shutoff valves, SOV and OSV, which shutoff the burn flow corresponding to cockpit demand and OSL demand respectively, may be optional, because the MEE system can shutoff the fuel supply to the engine by powering off the fuel pump motor.

CONTROL SYSTEM SIMULATION OF THE MEE

To evaluate the feasibility of the MEE STEP 1, an electrical fuel system, a control system simulation using the Matlab/Simlink simulation tool was conducted. The main objectives were to investigate the feasibility of the Active-Active redundant control of the dual motor system for the fuel pump and EMA. In the Active-Active control, both channels are in operation and each utilizes each feedback signal. The difference between the feedback signals due to sensor accuracy or other factors might affect the stable control of the fuel flow or actuator stroke. Simple transfer function models of the electrical fuel pump and EMA were used in the simulation to investigate the influence of the difference between the feedback signals.

(a) Simulation for the electrical fuel pump

A simulation block diagram is shown in Fig. 11, in which torque summing methodology is utilized for the Active-Active control of the dual motor of the fuel pump. The control system consists of "A" and "B" channels of the motor speed control loop. The output torque from each of the motors is accumulated and transmitted to the fuel pump shaft. Each control loop has a feedback sensor for the motor rotor angle, which is converted to the motor speed and fed back to the motor control loop in the controller. Simulation was conducted both with and without error in the rotor angle feedback signals between the "A" and "B" channels.

Figure 12 shows the simulation result of the step response. Figure 12 (a) is the result assuming no error in the rotor angle feedback signals between the "A" and "B" channels. Figure 12 (b) is the result assuming an error. As shown in both Fig. 12 (a) and (b), the motor speed feedback signals in the "A" and "B" channels are consistent and the motor speed is controlled in very stable condition. This is because the feedback signal in the motor speed control loop is derivative of the rotor angle sensor output, whereupon the difference between the sensor output signals can be cancelled.

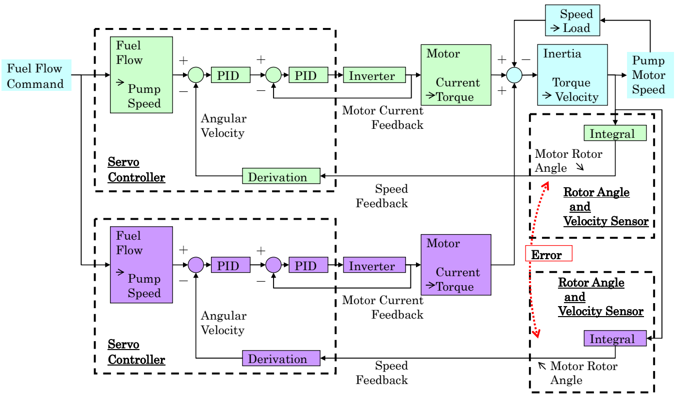
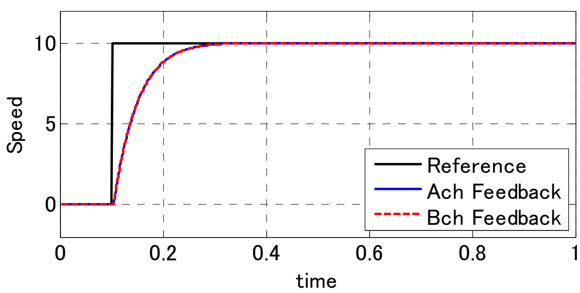
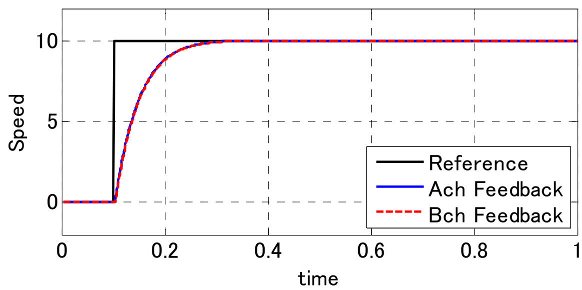


Figure 11 Simulation block diagram for the electrical motor-driven fuel pump



(a) Step response without feedback error between channels



(b) Step response with feedback error between channels

Figure 12 Simulation result of the fuel pump

(b) Simulation for the EMA

A simulation block diagram is shown in Fig. 13. Speed summing methodology is utilized for the Active-Active control of the EMA dual motor system. The control system consists of "A" and "B" channels of the actuator stroke control loop. The motor speed of each channel is totaled by a speed summing mechanism and converted to stroke speed via a ball screw, whereupon the actuator stroke speed and position are determined. Each control loop has a feedback sensor for the actuator stroke. Simulation was conducted both with and without error in the actuator stroke feedback signals between the "A" and "B" channels.

Figure 14 shows the simulation result of the step response. Figure 14 (a) is the result assuming no error in the actuator stroke feedback signals between the "A" and "B" channels. As shown in Fig. 14 (a), the stroke feedback signals in the "A" and "B" channels are consistent and the actuator stroke is controlled in a very stable condition, as is the actuator speed. Figure 14 (b) shows the step response in case of an error in the feedback stroke signals. As shown in Fig. 14 (b), the actuator stroke remains stable, but the speed feedback signals reveal constant offset between the "A" and "B" channels, which means that the "A" and "B" channel motors continue to rotate in opposite directions at equivalent speed, while the actuator stroke remains in the same position.

The EMA simulation indicates that the control logic of the Active-Active control for the speed summing actuator requires further investigation.

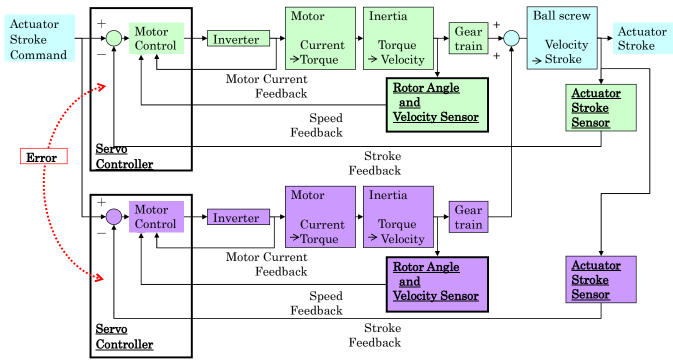
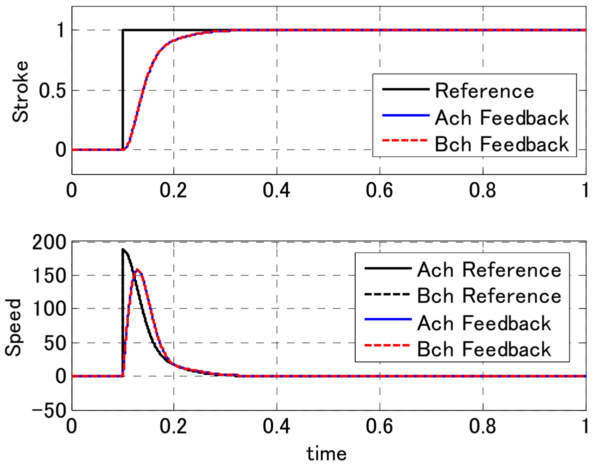
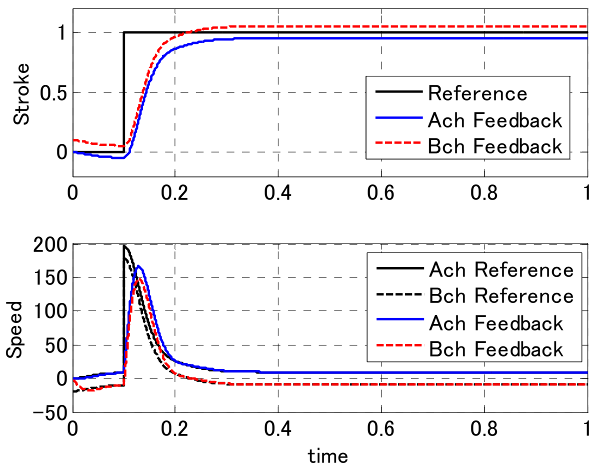


Figure 13 Simulation block diagram for the EMA



(a) Step response without feedback error between channels



(b) Step response with feedback error between channels

Figure 14 Simulation result of the EMA

CONCLUSION

The new MEE system is a greatly beneficial approach to reduce fuel burn of the engine and CO_2 emissions from the aircraft. A feasibility study and control system simulation was conducted for STEP 1 of the MEE, i.e. the electrical motor-driven fuel pump system. The results are as follows:

(A) The MEE reduces SFC by about 0.4% by improving fuel pump system efficiency.

(B) The MEE reduces SFC by about 0.6% by eliminating ACOC, which worsens engine efficiency by wasting fan discharge air.

(C) The MEE accomplishes a complete one fail operational/two fail safe control system by introducing a unique Active-Active control architecture and a fault-tolerant design for the redundant motor system.

(D) The MEE minimizes the engine overspeed and IFSD rate via a unique overspeed prevention system and simplification of the control system components.

(E) The estimated control system weight increases about 10%, but a plan for further reduction of the system weight is available.

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